Work Package 2 Final report (2010-2015)

Field experiments for quality digestate and compost in agriculture

Work Package 2 Report – Digestate Nitrogen Supply and Environmental Emissions

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ADAS

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Executive summary

The mean nitrogen (N) use efficiency (NUE) of spring bandspread food-based digestate measured in replicated field experiments was 54 ± 7% of total N applied. This was reduced to 13 ± 4% of total N applied when food-based digestate was bandspread in the autumn, highlighting the effect of N losses via overwinter nitrate leaching. Manure-based digestate applied in spring had a mean NUE of 52 ± 8% which decreased to 15 ± 6% of total N applied for autumn applications. For both materials, there was considerable variation between the NUE results obtained from the individual experimental sites; however, this was not surprising given the complex systems represented by the 15 experimental sites, including differences in soils, cropping, weather and digestate properties, and is commonly observed in experiments with other organic materials (e.g. livestock slurries).

MANNER-*NPK* estimates of NUE compared well with the field measurements, indicating that this is a useful tool for farmers and advisors who want to account for the nitrogen content of food-based and manure-based digestates when developing fertiliser strategies. However, there is scope for the MANNER-*NPK* estimates to be further improved by incorporating information on environmental N losses from digestates into the MANNER-*NPK* calculation algorithms. Importantly, data on digestate composition and NUE obtained in this study could be included in the forthcoming revisions to the Fertiliser Manual (RB209) to ensure that advice for farmers and advisors on digestate utilisation is up to date and robust.

Ammonia emissions were greater from applications of food-based digestates (*c*.40% of total N applied) than from livestock slurry (*c*.30% of total N applied); this is partly due to the higher ammonium content of the food-based digestate and partly to its elevated pH (mean 8.3). The majority of the ammonia losses occurred within 6 hours of spreading highlighting the importance of rapid soil incorporation as a method for preventing N losses via this pathway. Compared with surface broadcast, ammonia emissions were reduced on grassland when the food-based digestate was applied via trailing hose (39 ± 6% reduction) and particularly when it was applied via shallow injection (50 ± 12% reduction). However, appropriate soil conditions are required for shallow injection to operate to its full potential (i.e. soils should not be too wet or stoney). On arable land bandspread applications did not reduce ammonia emissions compared to broadcast applications, which were incorporated within 24 hours of application.

Because of the potentially important contribution that digestates could make in future to overall UK ammonia emissions, additional work is required to investigate alternative methods to further reduce ammonia emissions to arable land (e.g. acidification) to maximise the nutrient value of digestate, without greatly increasing costs or incurring other dis-benefits.

Nitrous oxide losses from the food-based digestates were low, with measured emission factors all less than the current IPCC default value of 1% (mean 0.45 ± 0.15%). This is in common with all of the organic materials measured and the results will contribute to future revisions of the UK inventory of nitrous oxide emissions from agriculture. Methane emissions from digestates were lower than from livestock slurry, which is probably because most of the 'available' carbon in the digestates had already been lost during the anaerobic digestion process. Carbon dioxide emissions were temporarily increased following digestate (and livestock slurry) applications. The reason for the small increase in carbon dioxide emissions was unclear; one possible explanation is that microbial respiration was stimulated by the supply of both readily available nitrogen and readily decomposable carbon. Overwinter nitrate leaching losses from food-based digestate were similar in magnitude to those from

pig slurry, but much greater than those from pig farm yard manure (FYM) or compost. Phosphorus (P) leaching losses were low and similar to those measured on the untreated control treatment, and *Escherichia coli* (*E. coli*) were not detected in the drainage waters.

The results from *DC-Agri* strongly suggest that digestate users should be advised, where practically possible, to apply digestates using precision application methods such as bandspreading/trailing shoe or shallow injection. Also, digestates should be applied when there is an N demand, commonly in the spring/summer, and should only be applied in the autumn to crops which are actively growing (e.g. oilseed rape and grass), with application rates controlled to match crop N requirements.

Atmospheric emissions (i.e. ammonia, nitrous oxide, methane) and leaching losses (nitrate and soluble P) from both green and green/food composts were found to be low (or not detected in the case of *E.-coli*) indicating that in these terms compost can be considered as an 'environmentally benign' material. Because of its valuable total N content, but low readily available N content, compost applications should be seen as a means to build up long-term (organic) soil N reserves rather than as a short-term replacement for mineral N fertiliser.

Contents

Acknowledgements

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The inspiration, enthusiasm, intellectual contribution, good humour and leadership of Professor Brian J. Chambers is also recognised; very sadly, Brian passed away before the project had been completed.

1. Introduction

1.1 Organic materials

In the United Kingdom, millions of tonnes of biodegradable organic materials are landfilled every year. Removing biodegradable waste from landfill will significantly reduce greenhouse gas emissions (in particular methane, which has a global warming potential around 20-fold greater than carbon dioxide) and thereby contribute to government targets to reduce climate change gas emissions. To this end, the EU Landfill Directive states that by 2020 the amount of biodegradable municipal waste disposed of in landfill sites must be reduced by 65%, compared with 1995 levels (EC, 1999). Organic materials diverted from landfill are available to be recycled to land, which has the potential to provide benefits in terms of the sustainable use of plant nutrients and the addition of organic matter to improve soil structural conditions. Additionally, treating organic materials via anaerobic digestion (AD) can help the UK meet important environmental goals, particularly the generation of renewable energy ('biogas') and reduction of greenhouse gas emissions. In addition to renewable energy, the AD process generates a nutrient-rich digestate ('biofertiliser'). As part of the UK's commitment to meet EU renewable energy targets by 2020, UK governments have put in place policies and strategies to increase the generation of renewable energy and treatment of food waste through AD.

1.2 Environmental implications

Nitrogen (N) is the single most important nutrient influencing crop yields on most mineral soils, with applications at the optimum economic rate typically doubling crop yields (Defra, 2010c). Making full allowance for the N supplied by organic materials is also a requirement of the Nitrate Vulnerable Zones (NVZs) Action Programme (SI, 2008; SSI, 2008; WSI, 2008). Hence, where a 'new' organic material such as digestate is being recycled to land, it is crucial to understand its N supply characteristics, as 'mismanagement' can result in yield penalties for farmers (through either underestimating or overestimating N supply) or undesirable environmental pollution through underestimated N supply. This is even more important for digestate than livestock slurries, as WRAP project OAV032 "Compost and Anaerobic Digestate Quality in Welsh Agriculture" showed that food-based digestates typically contained *c.*90% of their total N content in a readily available form, in contrast to pig slurry which has *c.*70% and cattle slurry which has *c.*45% in readily available form (Defra, 2010c).

There is a need to provide robust information on the crop available N supply from digestate and compost applications to give farmers confidence to allow for the nutrients supplied when drawing up nutrient management plans, and to provide robust scientific evidence to calculate greenhouse gas (GHG) emission savings through displaced manufactured fertiliser N use.

In addition to investigating the beneficial aspects of applying organic materials to land, it is essential that the application (agricultural or otherwise) is truly beneficial and is not harmful to the environment (i.e. soil, water and air quality) or human health. The European Nitrogen Assessment (Sutton *et al.,* 2011) highlighted how the overall environmental costs of all N losses in Europe (estimated at €70–€320 billion per year at current rates) outweigh the direct economic benefits of N in agriculture, due largely to loss of air quality and water quality. The land application of organic materials therefore needs to be carefully managed to maximise their nutrient value and minimise their impact on the wider environment (i.e. air and water quality). Ammonia (NH_3) emissions to air contribute to acid deposition and can cause eutrophication of sensitive ecosystems. Nitrous oxide (N_2O) is a greenhouse gas with a global warming potential *c.*300-fold greater than carbon dioxide (IPCC, 2006). Moreover, the UK Greenhouse Gas Emissions Inventory (2006) estimates that *c.*65% of N_2O produced in the UK comes from agriculture, with the majority emitted from soils following N applications (e.g. manufactured fertiliser N, organic materials and urine from grazing returns) to land. The remaining third of agricultural N_2O is emitted indirectly from soils following re-deposition of emitted ammonia and from leached nitrate. Additionally, the application of digestate and compost to land has the potential to impact on water quality, as a result of nitrate and phosphorus losses in surface run off and drainage water flows, and microbial pathogen losses to surface water systems.

The UK Government is committed to reducing N emissions (i.e. ammonia, nitrous oxide and nitrate) to the wider environment, in order to comply with existing and forthcoming Directives, Protocols and Plans (e.g. EC Nitrates Directive, Water Framework Directive, National Emission Ceilings Directive, Integrated Pollution Prevention and Control Directive, the Kyoto Protocol and Low Carbon Transition Plan). There is a recognised need to establish a robust scientific evidence base on the nutrient supply properties of digestate and compost applications to land. In particular, the N supply characteristics of contrasting digestate types (i.e. food-based, manure-based and crop-based) to ensure that policies to limit diffuse pollution from agriculture do not reduce one pollutant at the expense of another, so called 'pollution swapping' (e.g. by reducing nitrate leaching losses at the expense of enhanced ammonia and nitrous oxide emissions). The key challenge is to develop *best management practices* that maximise crop N utilisation, whilst minimising environmental emissions of ammonia, nitrous oxide and nitrate etc. i.e. maximising the so called 'win-win' situations. This not only has the potential to improve crop yields, but will also lead to reductions in the use of manufactured fertiliser N, providing both cost and GHG emission savings.

1.3 Overall programme objectives

The overall objective of the *DC-Agri* experimental programme was to:

- **Quantify the effects of contrasting digestate and compost applications on soil and crop quality, crop available nitrogen supply and emissions to the air and water environments.**

The project had two separate work packages (WP) to achieve this aim, plus a third WP delivering a comprehensive knowledge exchange programme on digestate and compost use in agriculture.

WP1: Quantification of the effects of repeated compost and digestate applications on soil and crop quality.

WP2: Quantification of the nitrogen supply characteristics of contrasting digestate and compost products (WP2.1), including the impact of digestate and compost additions on nitrous oxide and ammonia emissions to air and leaching losses (nitrate, phosphorus and microbial pathogens) to water (WP2.2), and the effect of bandspread/shallow injected digestate and slurry application techniques on fertiliser N replacement values, and crop yields and quality (WP2.3).

This report covers WP2.

1.4 WP2 Objectives

The aim of this work package was to investigate the fate of N supplied by digestate from Biofertiliser Certification Scheme accredited sites or those producing digestate meeting PAS110 minimum criteria and by compost from Compost Certification Scheme accredited sites in comparison with farmyard manure (FYM) and livestock slurry.

The specific objectives were to:

- Determine the crop available N supply from digestate (food and manure-based) across different application timings to a range of arable and grassland crops throughout Britain;
- Quantify the environmental emissions, following the application of digestate and compost, to the air and water environments; and
- Quantify the effect of bandspread/shallow injected digestate and slurry application techniques on fertiliser N replacement values, and crop yields and quality.

2. WP2.1 Nitrogen supply characteristics of contrasting digestate and compost products

2.1 Methodology

2.1.1 Experimental sites

Experimental sites were established at 15 locations on a range of contrasting soil types and agroclimatic zones across Britain (Table 2.1; Figure 2.1).

To characterise each site, representative topsoil samples (0-15cm at tillage sites and 0-7.5cm at grassland sites) were taken from each experimental block of plots prior to the start of the experiment. The soil samples were taken by following the pattern of a letter 'W' and taking 25 sub-samples at regular intervals from each replicate block (Defra, 2010b). The sub-samples were then bulked to form one representative sample per block and submitted for laboratory analysis of pH, sand (%), clay (%), silt (%), extractable phosphorus (P), extractable potassium (K) and extractable magnesium (Mg), extractable sulphate - sulphur (SO_4-S), total nitrogen (N) and organic carbon (C); see Appendix I (Table 1).

Table 2.1. Characteristics and cropping at the digestate N response sites.

Site		Soil textural group		Annual rainfall (mm)	Crop[+] and harvest year
		Cross-compliance soil group	% clay		
1	Aberaeron	Medium	29	1,298	G (2014)
2	Aberdeen	Sandy/light	14	791	SB (2013)
3	Ayr	Medium	23	1,190	G (2011)
4	Beith	Medium	31	1,341	G (2014)
5	Brawdy	Medium	27	679	WW (2011)
6.	East Malling	Sandy/light	14	713	WB (2013)
7.	Gleadthorpe	Sandy/light	6	581	POTS (2011)
8	Harper Adams	Sandy/light	12	687	WOSR (2013)
9	Loddington	Heavy	37	630	WW (2011)
10	Morpeth	Medium	32	692	G (2013)
11	Newark	Medium	36	587	G (2014)
12	North Wyke	Heavy	38	1,350	G (2012)
13	Pwllpeiran	Medium (heavy)	28	975	G (2012)
14	Wensum DTC*	Sandy/light	<18	594	WB (2012)
15	Devizes (Hampshire Avon River Catchment*)	Chalk/limestone	31	847	WW (2013)

[+] G = grassland (first cut); WW = winter wheat; WB = winter barley; POTS = potatoes; WOSR = winter oilseed rape; SB = spring barley

* Linked to Defra Demonstration Test Catchment (DTC) project

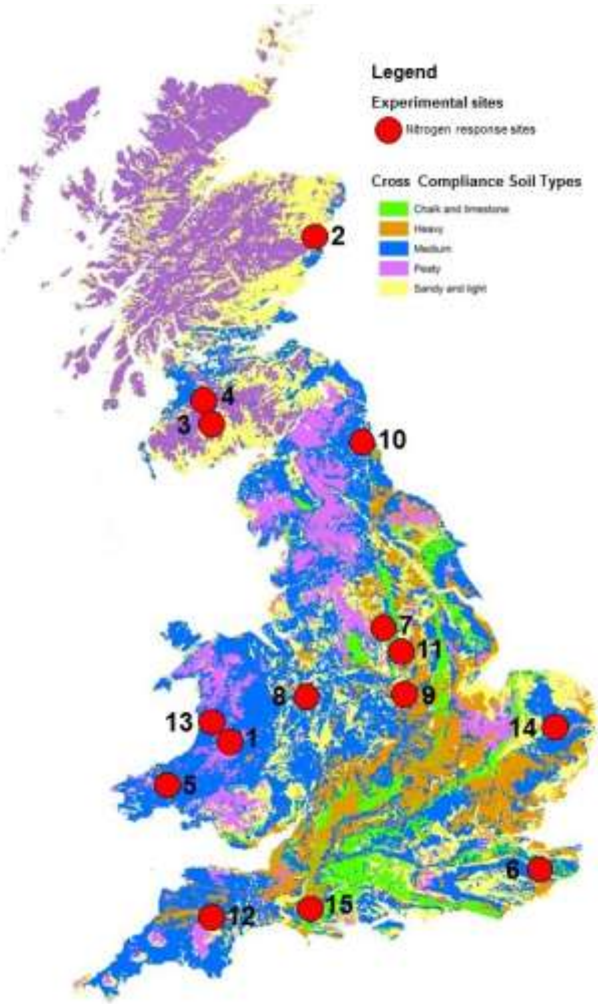

Figure 2.1. Location of the digestate N response sites.

Table 2.2. Organic material and fertiliser N response treatment details.

Treatment No	Treatment details
1	Untreated control
2	Autumn applied food-based digestate
3	Spring applied food-based digestate
4	Autumn applied manure-based digestate
5	Spring applied manure-based digestate
6	Autumn applied livestock slurry
7	Spring applied livestock slurry
8	Manufactured fertiliser at 50 kg N/ha arable/ 30 kg N/ha grass
9	Manufactured fertiliser at 100 kg N/ha arable/ 60 kg N/ha grass
10	Manufactured fertiliser at 150 kg N/ha arable/ 90 kg N/ha grass
11	Manufactured fertiliser at 200 kg N/ha arable/ 120 kg N/ha grass
12	Manufactured fertiliser at 250 kg N/ha arable/ 150 kg N/ha grass

Note: for the grassland sites (sites 8-12), organic material N response was calculated based on the response of the first grass harvest (cut) only after organic material application

2.1.2 Treatments and design

The organic material and fertiliser N response treatments applied at each site are shown in Table 2.2. At each site, there were three replicates of each treatment and untreated control arranged in a randomised block design (36 plots in total); with the exception of site 4 (Gleadthorpe), which had four replicates, due to greater experimental variation in potato crops compared with combinable crops/grassland. The fertiliser N response and control plots were randomised as narrower plots within the same replicate block as the larger digestate/slurry plots. The digestate and slurry plots were 12m wide by 12-24m long, whilst the fertiliser N and control plots were 4m wide by 12-24m long; at Gleadthorpe, each plot consisted of three 10m long potato beds. At sites where emission measurements were to be made (sites 1, 4, 11, 13 & 14) the organic material and fertiliser plots were 3-7m wide by 8-15m long, with the organic material plots orientated 20 degrees to the vertical (to allow for correct placement of wind tunnels to measure ammonia emissions – see Section 3). Sites 12, 13, 14 were part of a wider Defra project (ACO116) investigating environmental emissions following a wide range of livestock manures (e.g. poultry manures, livestock slurry, farmyard manures), thus these additional treatments were included in the wider experimental design.

The food-based digestates were from Biofertiliser Certification Scheme certified sites (or from sites working towards certification) and the manure-based digestates, cattle or pig slurries were sourced locally to each site. The digestates and slurries were applied via commercial precision application equipment; either the ADAS bandspreader (Plate 2.1) or a local contractor using a trailing hose/shoe as applicable (at sites 1, 4, 11, 13 & 14 the ADAS small plot applicator was used and at site 12 applications were made by hand, to allow gaseous emissions measurements to be made using the wind tunnel technique – see Section 3). The amount of material applied to each plot was measured via flow meter and cross-checked using weigh pads or a weighbridge, so that the application rate to each plot could be accurately determined. Target application rates were in the range 100-150 kg/ha total N to be representative of the rate that would be applied commercially and also to target the 'sensitive' area of the N response curve (50-100 kg/ha crop available N). All applications were compliant with the requirements of the NVZs Action Programme; *i.e.* the organic manure N field-limit of 250 kg/ha total N (SI, 2015; WSI, 2013).

Plate 2.1. ADAS bandspreader application equipment for digestate and slurry.

Fertiliser N applications to the N response plots were made by hand at appropriate timings and splits in the spring of each cropping/experimental year and were based on advice from a Fertiliser Adviser and Certification and Training Scheme [FACTS] qualified adviser.

At most sites, the digestates and livestock slurry were applied in autumn (before the start of the NVZ closed spreading period for high readily available N materials) and in spring. At the Harper Adams experimental site (winter oilseed rape), a delayed cereal harvest due to 'wet' weather resulted in the oilseed rape crop being drilled late and before the organic materials could be applied. Subsequent wet weather and soil conditions precluded the application of organic materials before the start of the NVZ closed spreading period. As a result, the digestates and slurry were applied on two separate occasions in early and late spring 2013. At the Gleadthorpe experimental site (potatoes), the digestates and slurry were applied early and immediately before bed-forming in spring 2011. At the Aberdeen experimental site (spring barley), digestates and slurry were applied in spring 2013, either before drilling or topdressed *c.*1 month after drilling. At Pwllpeiran weather conditions delayed manufactured N and organic material applications to late spring (May 2012).

2.1.3 Organic material analysis

At each site and application timing, a representative sample of each organic material type from each experimental block was taken (*c.*2 litres or 2 kg per replicate block), giving three replicate samples of each material per site. These samples were subsequently analysed for pH, dry matter (DM), total N, ammonium-N, extractable P, K, Mg and S, and total Ca using standard methodologies (MAFF, 1986).

2.1.4 Crop management

The grass and arable crops were grown according to best farm practice using commercially recommended seed rates, with crop protection products applied as needed and according to good agricultural practice to control weeds, pests and diseases equally across all treatments. No manufactured N fertiliser was applied to the organic material treatments, but all treatments, including the untreated control, had manufactured fertilisers (P_2O_5, K_2O & SO_3) applied based on the requirements of the untreated control (Defra, 2010b) to ensure that only N limited plant growth. All recommendations were calculated by a FACTS qualified adviser.

2.1.5 Harvest

Crop yields (grain/seed, grass, tuber yields and DM content) were measured each year using plot scale equipment i.e. for cereals and oilseed rape (Sites 2, 5, 6, 8, 9, 14 & 15) a small plot combine was used, for grass yields at first cut (Sites 1, 3, 4, 10, 11, 12 & 13) a mechanical grass harvester was used, and the potatoes at Site 7 were hand-harvested. Samples of grain/seed, grass and tubers were sent for analysis of total N, P, K, S and Mg content.

2.1.6 Fertiliser N replacement values and N use efficiency

The crop yield response to applied N fertiliser was compared with the organic material N supply (Sylvester-Bradley *et al.*, 1984), to calculate the N fertiliser replacement value of the organic materials at each site and application timing. The crop yield response to manufactured fertiliser N was described using a linear plus exponential function ($yield=a+br^N+cN$; George, 1984) and the goodness of fit (i.e. the r^2 value of the fitted curve) was recorded. By comparing the yield on each organic material treatment to the equivalent yield obtained on the fertiliser N response treatments, the amount of fertiliser N required to produce that yield was derived (i.e. the fertiliser N replacement value – FNRV – of the organic material). The nitrogen use efficiency (NUE) is the FNRV expressed as a percentage of the total N applied in the organic material (Figure 2.2). In this theoretical example, 250 kg/ha of total N was applied by an organic material application. The crop yielded 7.8 t/ha, so using the curve produced from the manufactured fertiliser N treatments a yield of 7.8 t/ha is equal to 125 kg/ha of applied fertiliser; 125 divided by 250 gives an N use efficiency of 50%.

Note: At Pwllpeiran weather conditions delayed manufactured N and organic material applications such that there was no yield response to N, but there was a crop N offtake response, NUEs were calculated using the 'N offtake method'. Here, a similar calculation was applied to that described above but using crop N offtakes as opposed to crop yields.

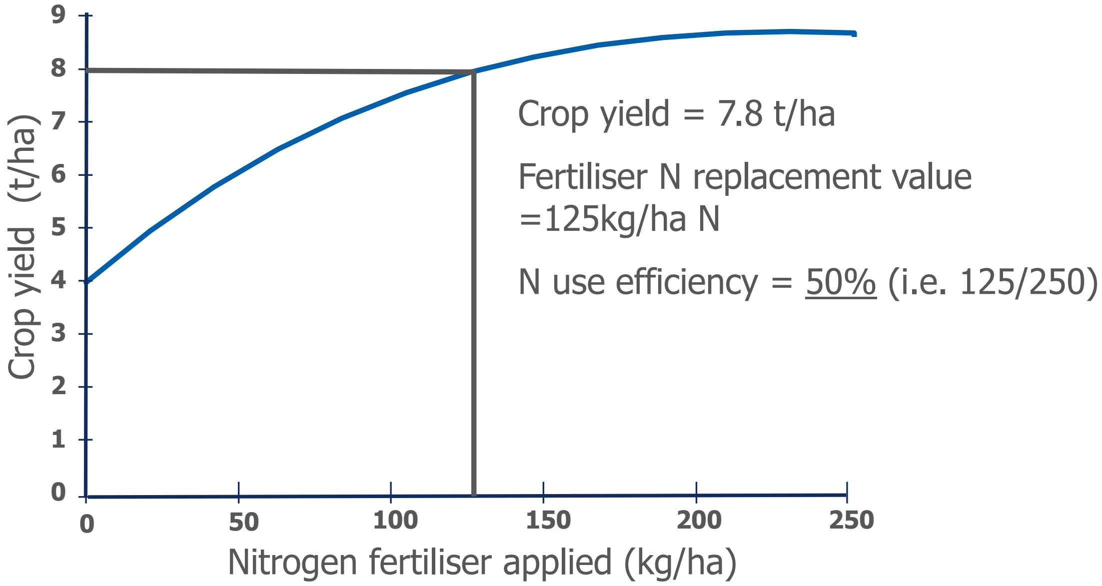

Figure 2.2. Example NUE calculation using a curve fitted to yields obtained on fertiliser N response treatments.

2.1.7 Statistical analysis

At each experimental site, differences between crop yields and nutrient offtakes were explored using conventional analysis of variance (ANOVA) and comparison of P statistics (quoted in the text). A separate ANOVA was carried out at each site, after which *post-hoc* testing was undertaken to evaluate which treatment means were different from each other using a Duncan's multiple range test (using Genstat version 12; VSN International Ltd, 2010). This test assigns different letters to treatment values which are significantly different from each other at the 5% level ($P<0.05$). In the tables of results and graphs, treatments which are statistically significantly different (at $P<0.05$) are marked with different letters. For example, if the food-based digestate treatment result is marked with 'a' and the cattle slurry treatment result with 'b', then these two treatments are different from each other. However, if the manure-based digestate treatment result was marked with 'ab', then it is not different from either the food-based digestate or the cattle slurry treatment results.

Additionally, the pooled nitrogen use efficiency (NUE) data from thirteen of N response experiments were analysed using ANOVA (*i.e.* a cross-site analysis was undertaken; the results from Aberdeen and Gleadthorpe were excluded from this analysis, as treatments were only applied on two occasions in the spring at these sites) to assess whether a particular treatment had a statistically significant effect at each site, and across all study sites.

2.2 Results

2.2.1 Organic material analysis

The mean chemical analysis of the digestates (food and manure-based) applied at the fifteen N response sites is shown in Table 2.3 (full details of the organic material analysis at each site including the analysed livestock slurry are given in Appendix I, Table 2). The analytical results from East Malling's food-based digestate have been excluded from the calculation of the mean, as the feedstock for this digestate was based on vegetable waste (including sweetcorn, maize and salad), which gave rise to a lower readily available N content compared to the other food-based digestates used in this study.

The food-based digestate had higher total and readily available N contents than the manure-based digestate (P<0.001 by 't test'; Table 2), with the latter having similar N contents to 'typical' values reported for cattle or pig slurry (i.e. RB209 values of 2.6 and 1.6 kg/t fw for cattle slurry and 3.6 and 2.5 kg/t fw for pig slurry, respectively; Defra, 2010b). Also, the pH of both the food and manure-based digestates was higher (mean pH 8.3 and 8.0) than typical cattle and pig slurry (mean pH 7.2 and 7.7; Chambers *et al.*, 2005) which can have important implications for N losses via ammonia volatilisation (see Work Package 2.2).

The nutrient analysis data for food-based digestates were similar to the 'typical' values in MANNER-*NPK*/PLANET, except for P_2O_5 and SO_3 (0.8 and 0.6 kg/t, respectively) which were higher than the previously published 'typical' value using identical analysis methods (Table 2.3), reflecting the influence that different feedstocks can have on the composition of the resulting digestates.

Table 2.3 Mean organic material analyses (2010-2014) from the WP2 experimental sites (standard errors in parenthesis), compared to 'typical values' used in MANNER-NPK/PLANET.

Determinand (kg/t fw[1] except where stated)	***DC-Agri* data**		**MANNER-*NPK*/PLANET**		
	Food-based digestate (n=28)[2,3]	**Manure-based digestate (n=24)[2]**	**Food-based digestate**	**Pig slurry-based digestate**	**Cattle slurry-based digestate**
pH	8.3 (0.05)	8.0 (0.07)	-	-	-
Dry Matter (%)	3.3 (0.29)	3.7 (0.50)	4.0	2.0	4.0
Total Nitrogen (N)	5.40 (0.27)	3.17 (0.28)	5.0	3.6	2.6
Readily Available N (RAN)[4] *% of total N*	4.04 (0.22) *75% (0.01)*	1.94 (0.24) *61% (0.03)*	4.0 *(80%)*	2.9 *(80%)*	1.4 *(54%)*
Total Phosphate (P_2O_5)	0.80 (0.08)	0.87 (0.14)	0.5	1.8	1.2
Total Potash (K_2O)	1.90 (0.06)	2.54 (0.17)	2.0	2.4	3.2
Total Magnesium (MgO)	0.14 (0.02)	0.51 (0.08)	0.1	0.7	0.6
Total Sulphur (SO_3)	0.62 (0.07)	0.65 (0.09)	0.4	1.0	0.7
Total Calcium (Ca)	1.20 (0.15)	1.14 (0.35)	-	-	-

[1] kg/t fw = kilograms/tonne fresh weight
[2] n=number of sites and seasons.
[3] Data from East Malling were not included as the feedstock was not typical of food-based digestates.
[4] Readily available nitrogen (ammonium-N)

2.2.2 Crop yields and nitrogen use efficiencies

Site 1: Aberaeron

The spring application of food-based digestate and cattle slurry increased (*P*=0.001) grass yields by 1.1-1.5 t/ha compared with the untreated control (Figure 2.3; Appendix I, Table 3). In comparison, the autumn applied food-based digestate and cattle slurry treatments increased grass yields by 0.4-1.5 t/ha compared with the untreated control (Figure 2.3; Appendix I, Table 3). The spring applied organic material treatments increased grass yield more than the autumn applications.

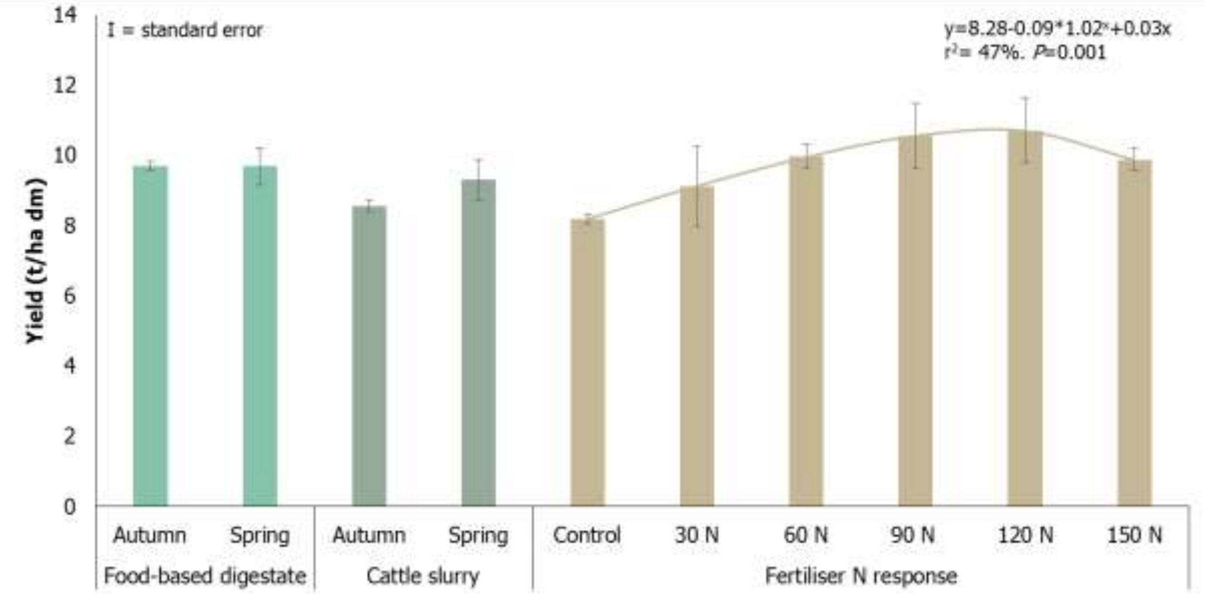

Figure 2.3. Aberaeron grass yields (t/ha dry matter).

The grass yield responded to manufactured fertiliser N applications (r^2 = 47%; Figure 2.3) and the NUE was calculated using the yield method. The NUE of the spring applied organic material treatments was numerically higher than the autumn treatments, although this could not be confirmed statistically (Figure 2.4).

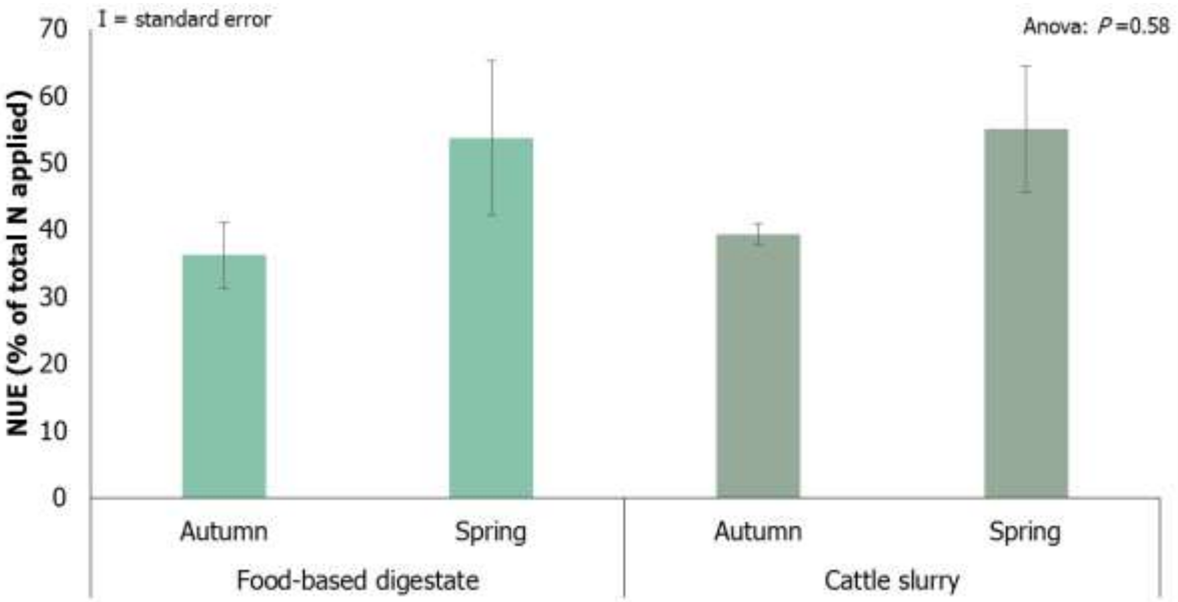

Figure 2.4. Aberaeron N use efficiency (% of total N applied) 'Yield method'.

Site 2: Aberdeen

The application (and soil incorporation) of food and manure-based digestate and cattle slurry before drilling in spring 2013, increased ($P<0.001$) spring barley yields by 1.6-3.5 t/ha compared with the untreated control (Figure 2.5; Appendix I, Table 3). In comparison, post-drilling (late spring) topdressed food and manure-based digestate and cattle slurry increased ($P<0.001$) spring barley yields by 1.0-2.4 t/ha compared with the untreated control (Figure 2.5; Appendix I, Table 3). One reason for the higher yields on the pre-drilled compared with the post-drilled applications could be that there were lower ammonia emissions (possibly related to cooler weather conditions) and hence greater crop available N supply. Alternatively, the N may have been applied to the post-drilled crop too late to translate into yield increases i.e. the crop could have been starved of N during the early growth stages.

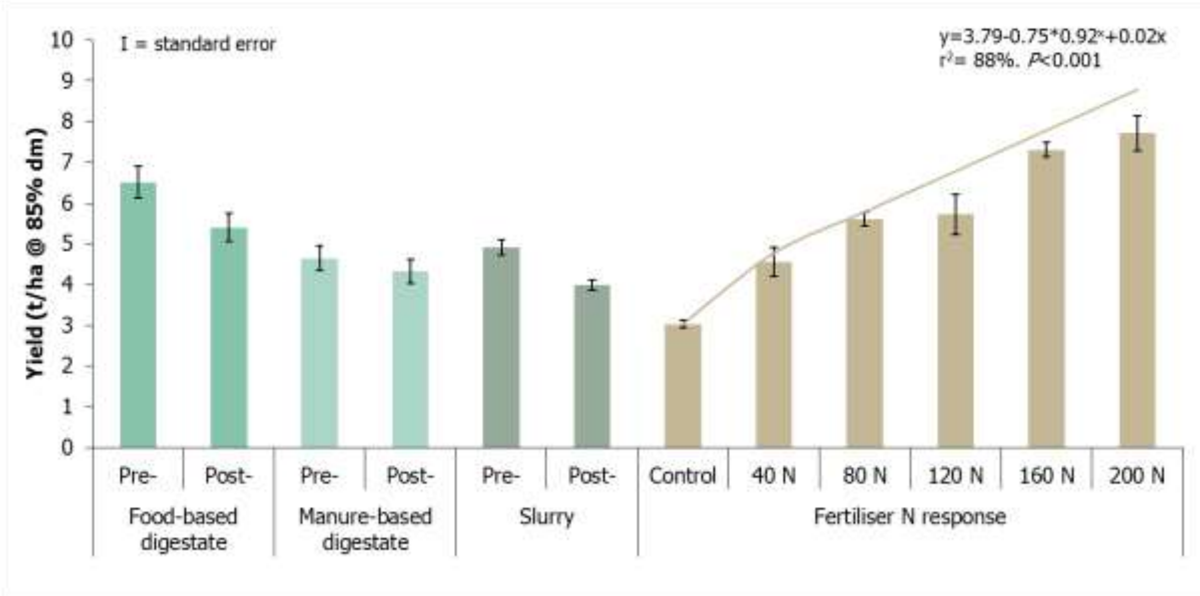

Figure 2.5. Aberdeen spring barley yield (t/ha @85% dry matter).

Spring barley grain yields responded to manufactured fertiliser N application (r^2= 88%; Figure 2.5) and NUEs were calculated using the yield method. The NUE of the pre-drilling applications of all treatments were numerically higher than the post-drilling applications, although this was only statistically significant for the cattle slurry applications ($P<0.05$ in Duncan's test).

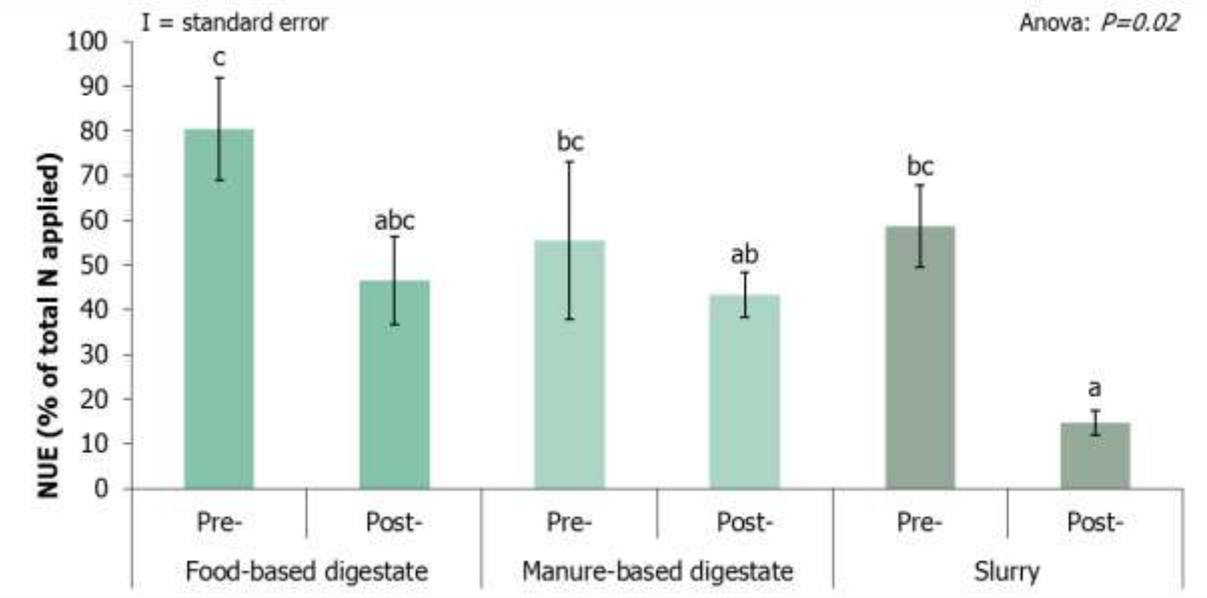

Figure 2.6. Aberdeen N use efficiency (% of total N applied) 'Yield method'. *Columns labelled with different letters are significantly different (P<0.05) from each other.*

Site 3: Ayr

The digestates, slurry and fertiliser N additions had no significant effect on first cut grass yields (*P* = 0.14; Figure 2.7), which was likely a reflection of higher than anticipated soil N fertility that resulted in a 'high' yield on the control (*i.e.* nil fertiliser N treatment) of *c.*8 t/ha (Appendix I, Table 3). As a result, NUEs could not be calculated for this site.

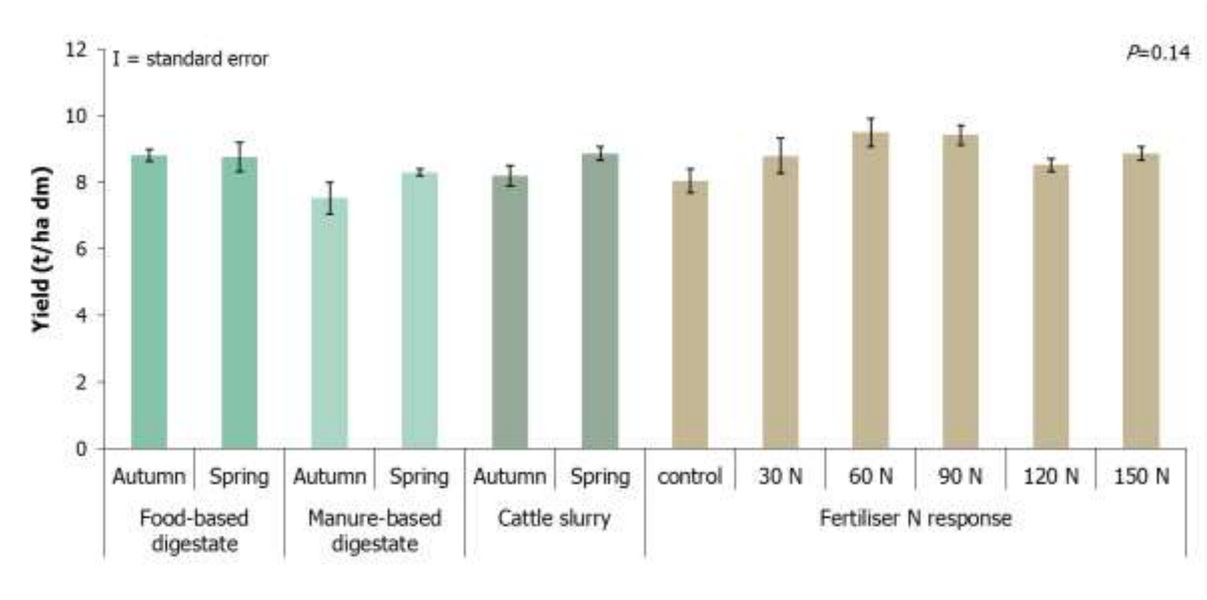

Figure 2.7. Ayr grass yields (t/ha dry matter).

Site 4: Beith

Although spring applications of food-based digestate and cattle slurry increased grass yields by 0.5-0.7 t/ha compared with the untreated control, these increases were not statistically significant (*P*=0.335; Figure 2.8; Appendix I, Table 3). The autumn applied food-based digestate and cattle slurry treatments had no effect (*P*=0.335) on grass yield (Figure 2.8; Appendix Table 3). The spring applied organic material treatments increased grass yield more than the autumn applications.

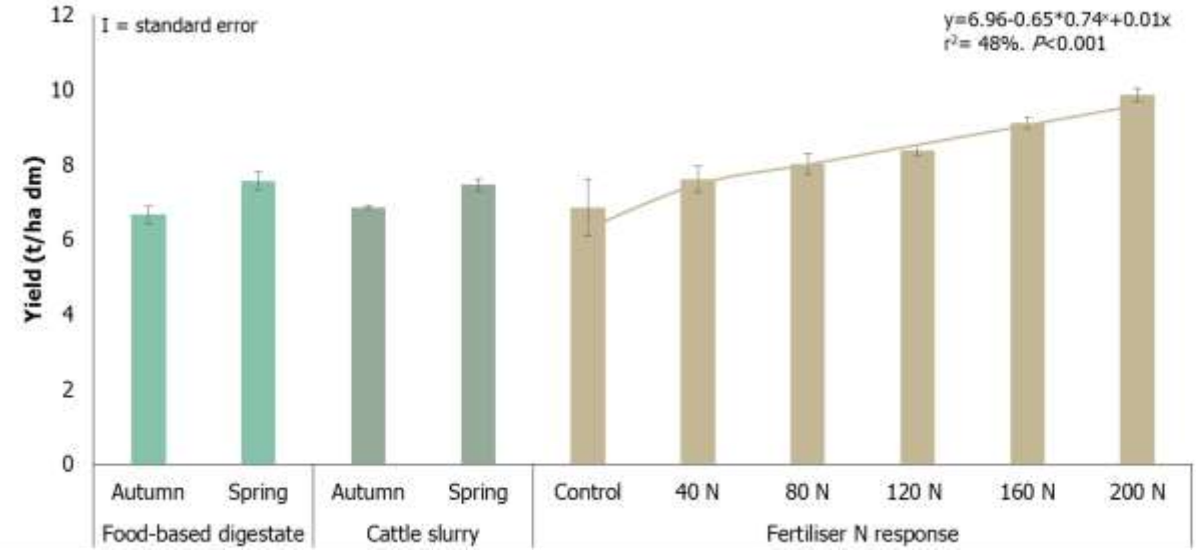

Figure 2.8. Beith grass yields (t/ha dry matter).

The grass yield responded to manufactured fertiliser N applications (r^2 = 48; Figure 2.8) and the NUE was calculated using the yield method. The NUE of the spring applied organic material treatments was higher (*P*<0.05 in Duncan's test) than the autumn treatments (Figure 2.9).

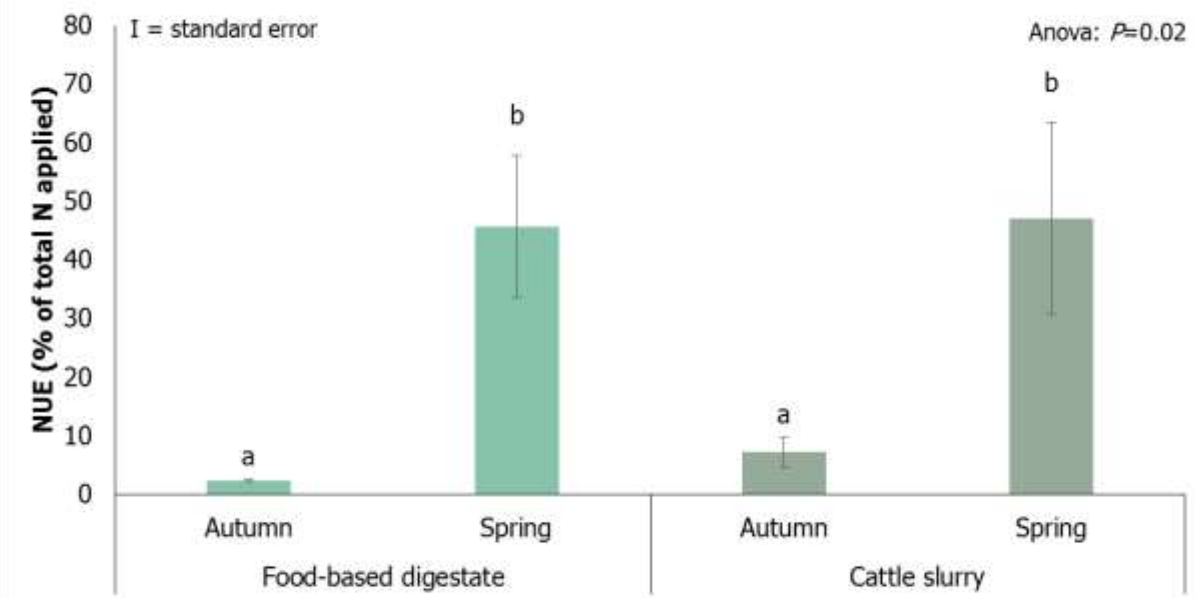

Figure 2.9. Beith N use efficiency (% of total N applied) 'Yield method'. *Columns labelled with different letters are significantly different (P<0.05) from each other.*

Site 5: Brawdy

The application of digestate (food or manure-based) or slurry in spring 2011 increased winter wheat yields by 1.6-2.6 t/ha compared with the untreated control (*P*<0.01). There were no significant differences in yield between the autumn applied digestate/slurry treatments and the untreated control, (Figure 2.10; Appendix I, Table 3).

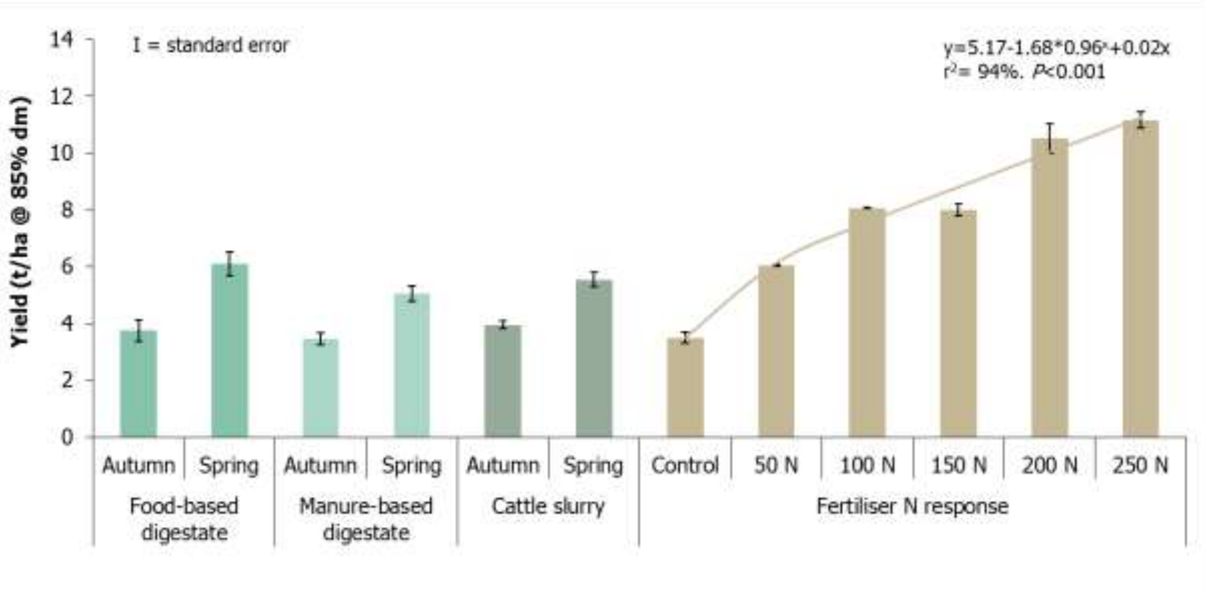

Figure 2.10. Brawdy winter wheat yield (t/ha dry matter@ 85% dry matter).

Winter wheat yields responded to manufactured fertiliser N (Figure 2.10 and NUEs were calculated using the yield method. The NUEs of the spring applied digestates and slurry were higher (P<0.05 in Duncans test) than the autumn treatments (Figure 2.11).

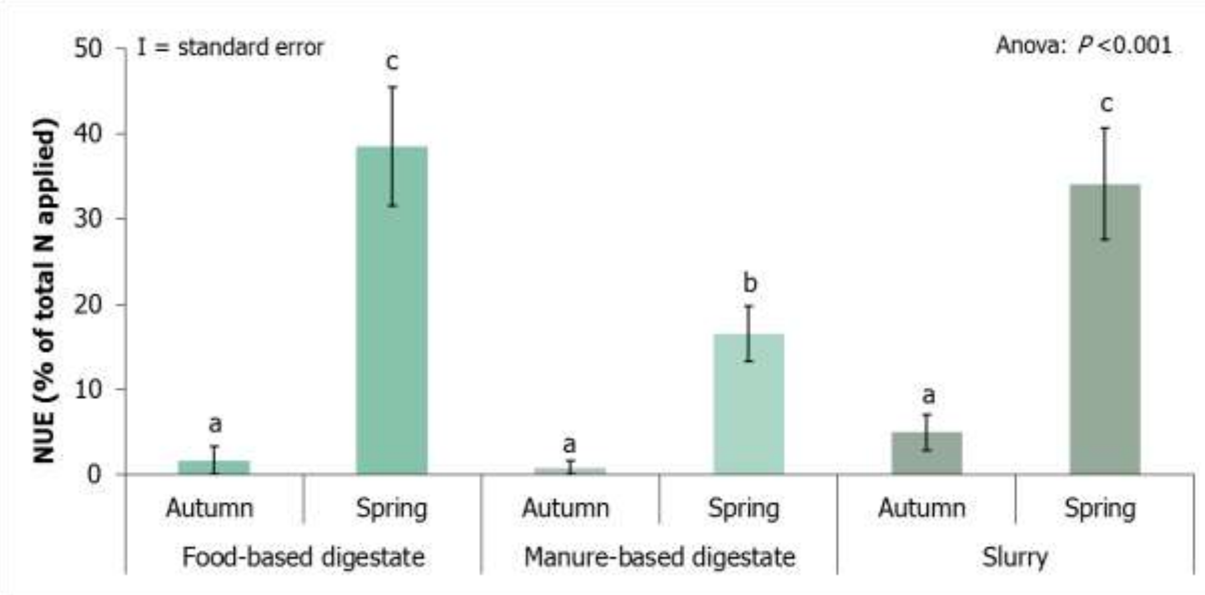

Figure 2.11. Brawdy N use efficiency (% of total N applied) 'yield method'. *Columns labelled with different letters are significantly different (P<0.05) from each other.*

Site 6: East Malling

The application of manure-based digestate in spring 2013 increased winter barley yields by 2.8 t/ha compared with the untreated control (P<0.01). In contrast, the autumn applied food-based and manure based digestate and cattle slurry treatments did not significantly increase winter barley yields (Figure 2.12; Appendix I, Table 3).

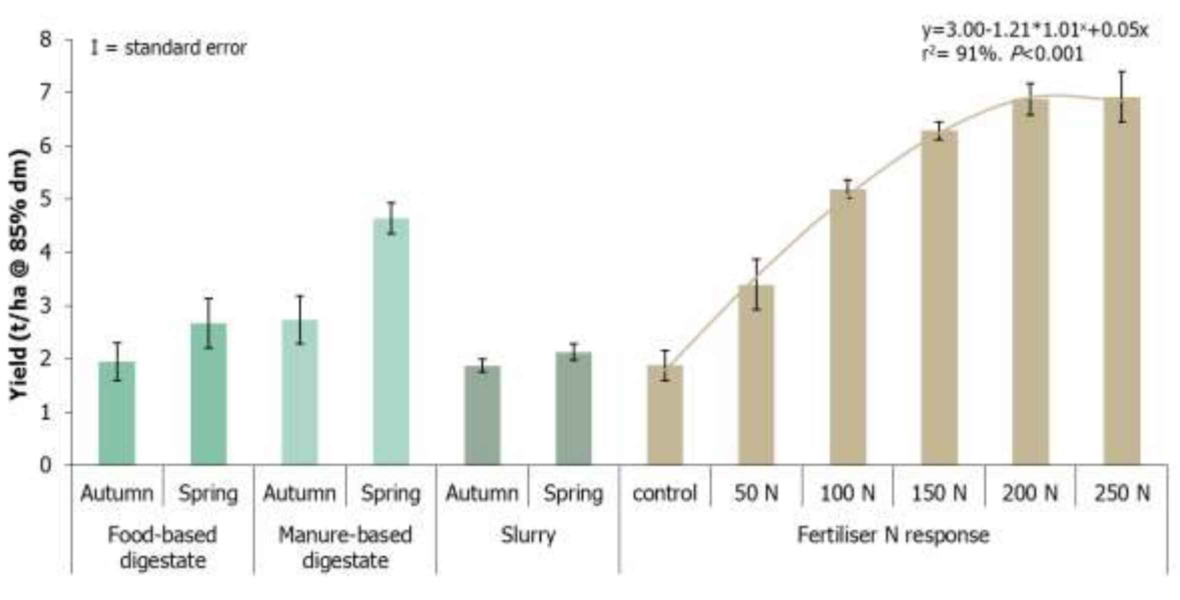

Figure 2.12. East Malling winter barley yield (t/ha @85% dry matter).

Winter barley yields responded to manufactured fertiliser N applications (r^2 = 91%; Figure 2.12) and NUEs were calculated using the yield method. The NUE of the spring applied manure-based digestate was higher (*P*<0.05 in Duncan's test) than the autumn application (Figure 2.13). The manure-based digestate at this site was largely based on pig slurry and had a 'higher' readily available N (RAN) content (*c.*85% of total N) than the food-based digestate (*c.*50% of total N), which had an 'atypical' RAN content due to a feedstock based on predominantly vegetable waste.

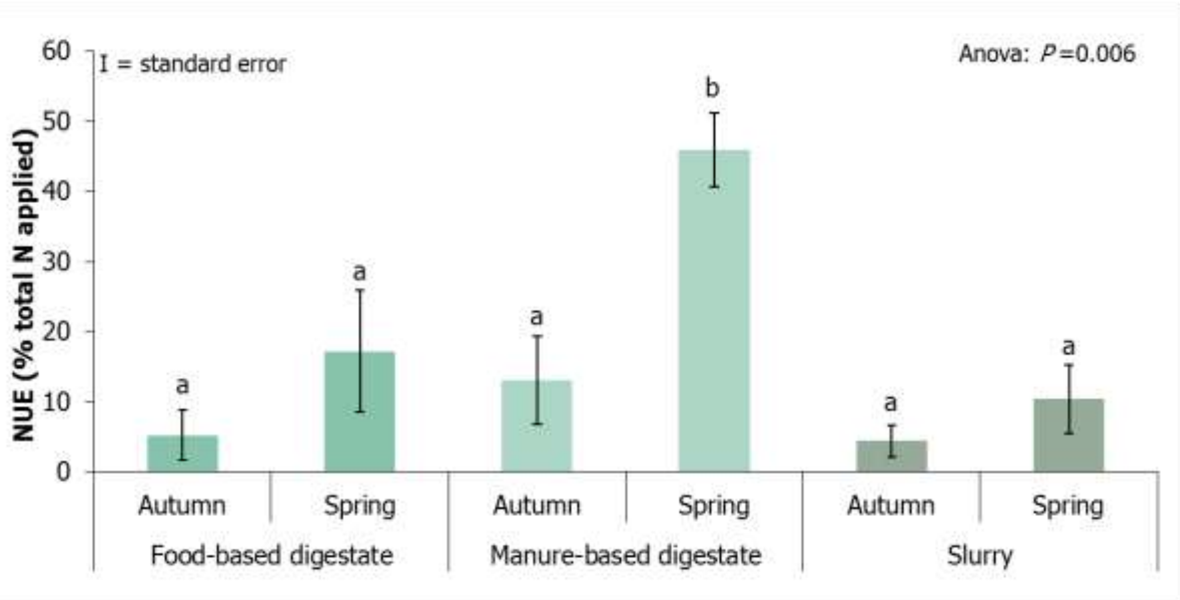

Figure 2.13. East Malling N use efficiency (% of total N applied) 'Yield method'. *Columns labelled with different letters are significantly different (P<0.05) from each other.*

Site 7: Gleadthorpe

The application of digestate (food or manure-based) or slurry in either early or late spring 2011 increased (*P*<0.01) potato yields by between 11-15 t/ha compared with the untreated control (Figure 2.14; Appendix I, Table 3).

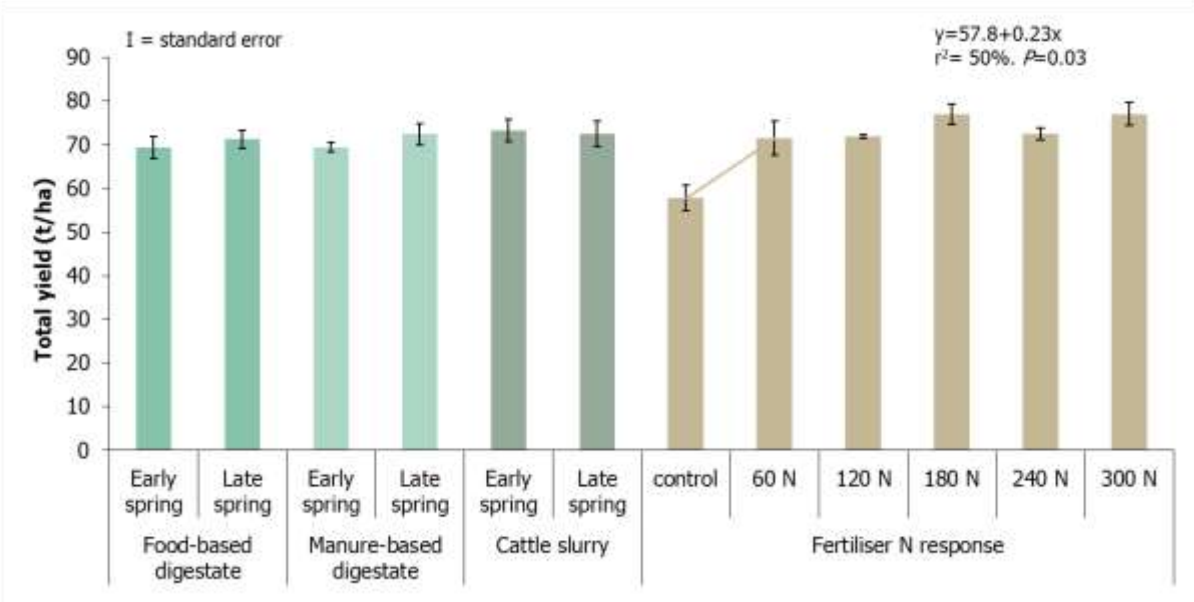

Figure 2.14. Gleadthorpe potato yields (t/ha dry matter). Note: Yields only responded to N fertiliser up to 60 kg/ha so were therefore described by a linear relationship.

Potato yields responded to manufactured fertiliser N applications up to 60 kg/ha (Figure 2.14) therefore NUEs were based on a linear response for manufactured fertiliser N between 0 and 60 kg/ha. There were no significant differences in NUE between the early and late spring digestate/slurry applications (P= 0.28; Figure 2.15), which is likely a result of there being little rainfall or variation in climatic conditions during this period.

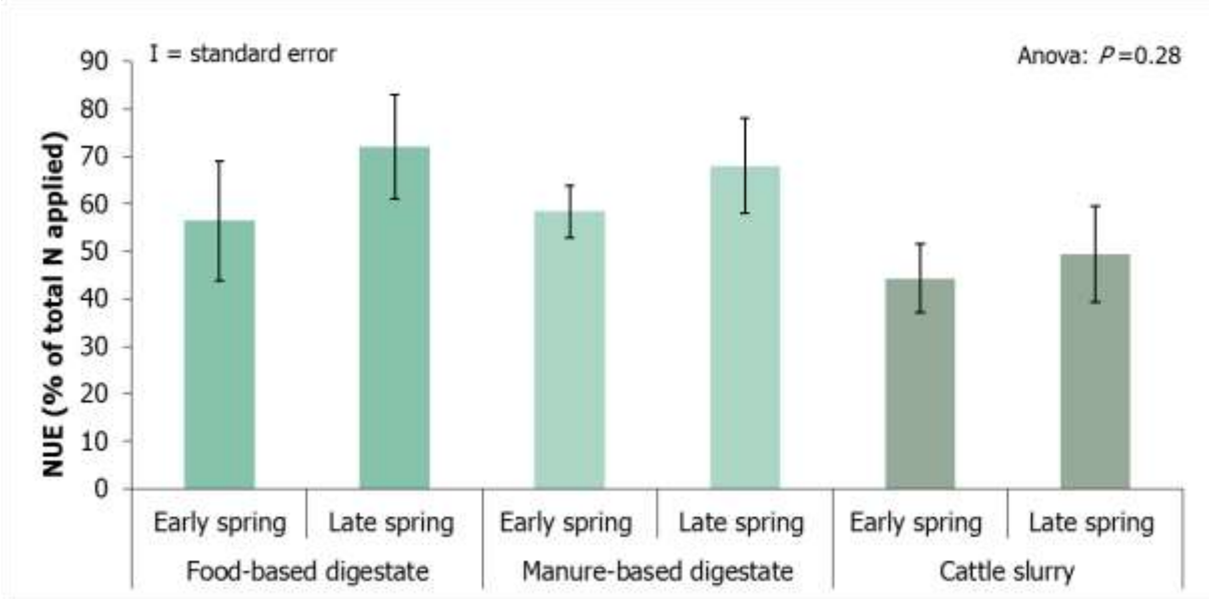

Figure 2.15. Gleadthorpe N use efficiency (% of total N applied) 'yield method'.

Site 8: Harper Adams

The digestate (food and manure-based) increased (P<0.01) oilseed rape yields by *c.*1 t/ha compared with the untreated control, but the slurry applications had no significant effect on yield (Figure 2.16; Appendix I, Table 3). The lack of yield response at the site resulted in a very shallow fertiliser N response curve, with the organic material treatments being at the top of the N response curve asymptote (Figure 2.16). As a result, we were unable to calculate NUEs at this site.

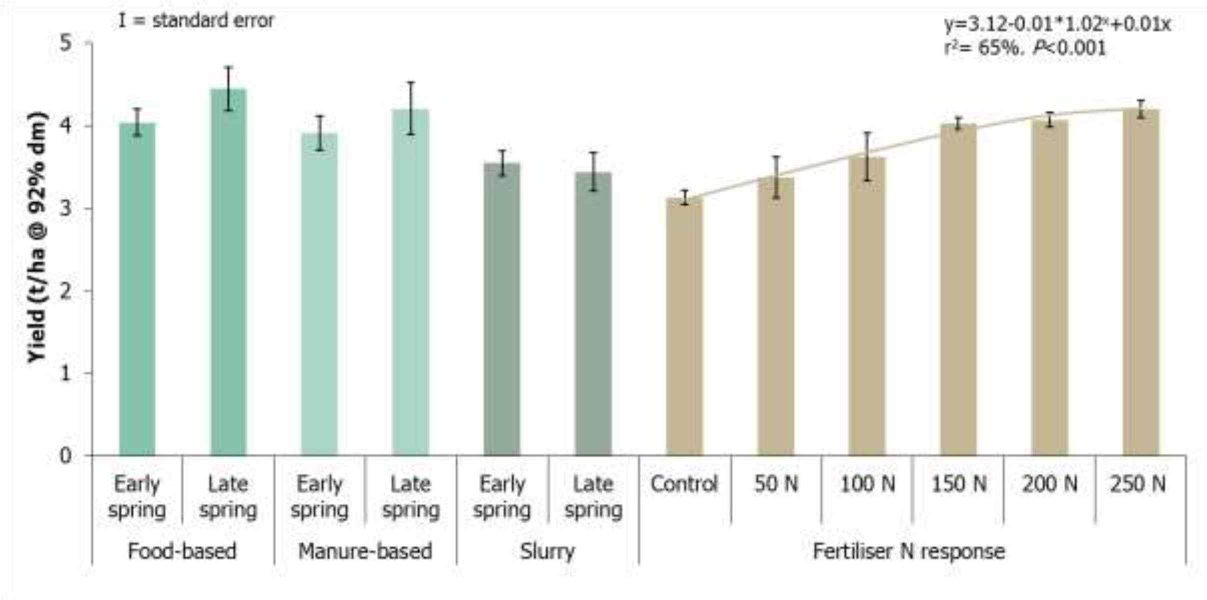

Figure 2.16. Harper Adams oilseed rape yields (t/ha dry matter).

Site 9: Loddington

The application of food-based digestate (in both autumn and spring) and manure-based digestate in spring 2011 increased winter wheat yields at Loddington (*P*<0.01) by 1.0-1.7 t/ha compared with the untreated control (Figure 2.17; Appendix I, Table 3).

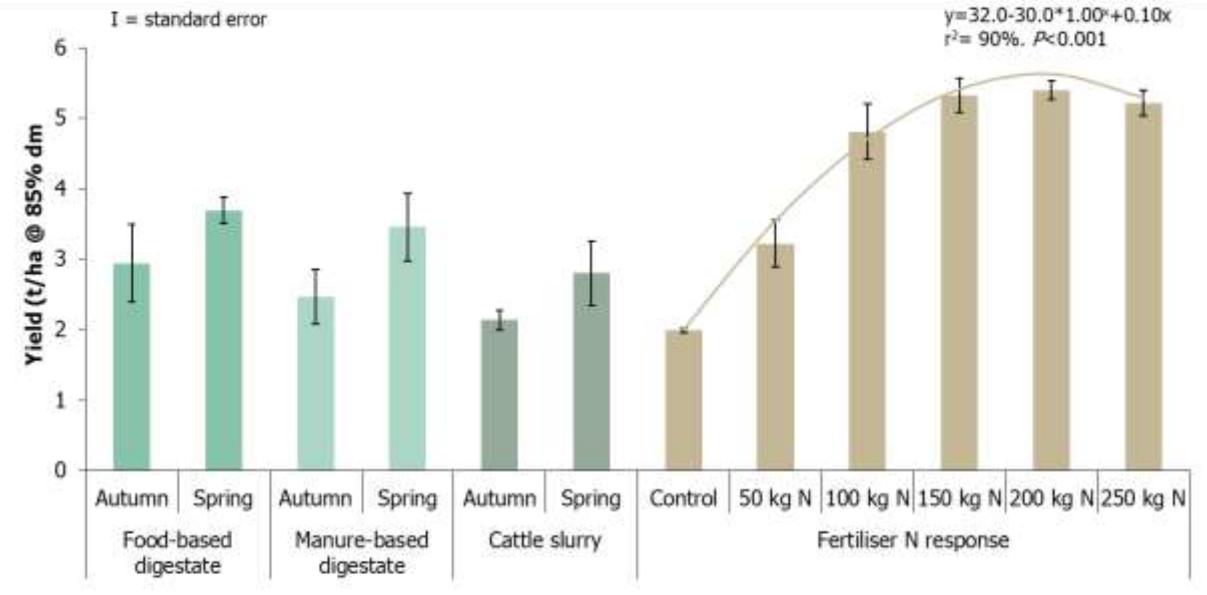

Figure 2.17. Loddington winter wheat yields (t/ha dry matter).

Winter wheat yields responded to manufactured fertiliser N applications (r^2 = 90%; Figure 2.17) and the NUE was calculated using the yield method. The NUE of the spring applied food-based digestate and slurry was higher (*P*<0.05 in Duncan's test) than for the autumn applied treatments (Figure 2.18). NUEs from the spring digestate applications ranged between 17 and 72% (mean = 46%), compared with 1 to 10% (mean = 6%) for the autumn applications.

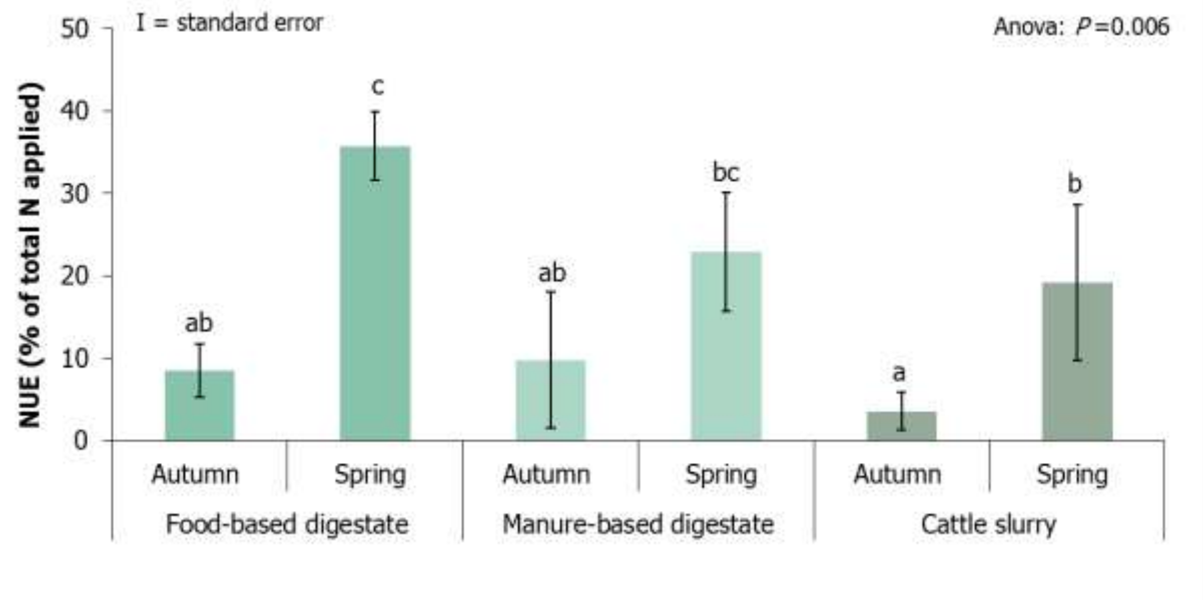

Figure 2.18. Loddington N use efficiency (% of total N applied) 'yield method'**.** *Columns labelled with different letters are significantly different (P<0.05) from each other.*

Site 10: Morpeth

The application of food-based digestate and manure-based digestate and cattle slurry in spring 2013 increased (*P*<0.001) grass yields by 1.8-4.9 t/ha compared with the untreated control (Figure 2.19; Appendix I, Table 3). In comparison, the autumn applied food-based digestate and cattle slurry treatments increased (*P*<0.001) grass yields by 1.0-3.0 t/ha compared with the untreated control (Figure 2.19; Appendix I, Table 3). The spring applied organic material treatments increased grass yield more than the autumn applications.

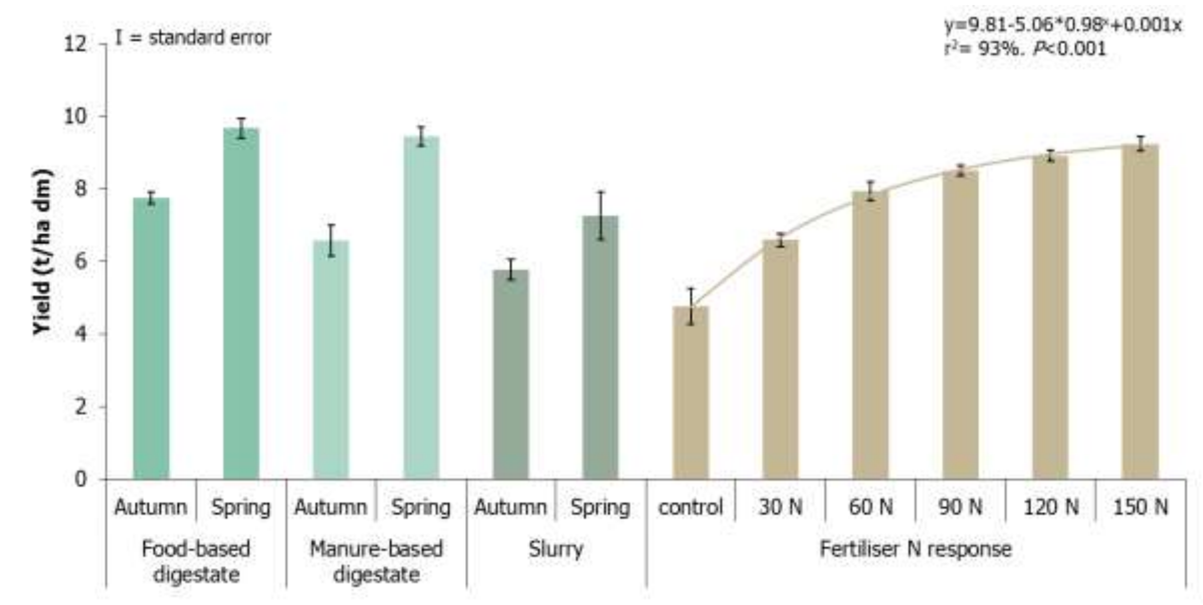

Figure 2.19. Morpeth grass yields (t/ha dry matter).

The grass yield responded to manufactured fertiliser N applications (r^2 = 93%; Figure 2.17) and the NUE was calculated using the yield method. The NUE of the spring applied digestate treatments was higher (*P*<0.01) than the autumn treatments (Figure 2.20). However, as yields were close to/above the top of the manufactured fertiliser N response treatments the estimated NUE of the spring food and manure-based digestate treatments should be treated with caution (Figure 2.20).

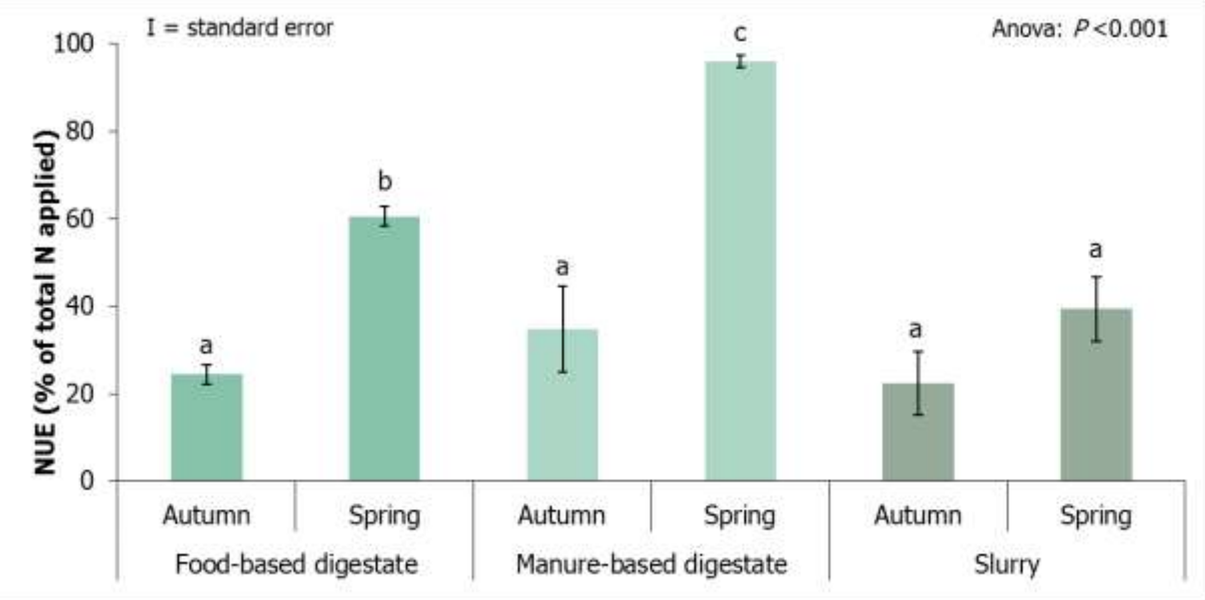

Figure 2.20. Morpeth N use efficiency (% of total N applied) 'Yield method'. *Columns labelled with different letters are significantly different (P<0.05) from each other.*

Site 11: Newark

The food-based digestate, cattle slurry and fertiliser N additions had no effect (*P*=0.829) on grass yields (Figure 2.21; Appendix 1, Table 3). This is likely a reflection of the late harvest (21st May 2014) caused by wet weather during May. Because neither grass yields nor grass N offtakes responded to fertiliser N additions, NUEs could not be calculated for this site.

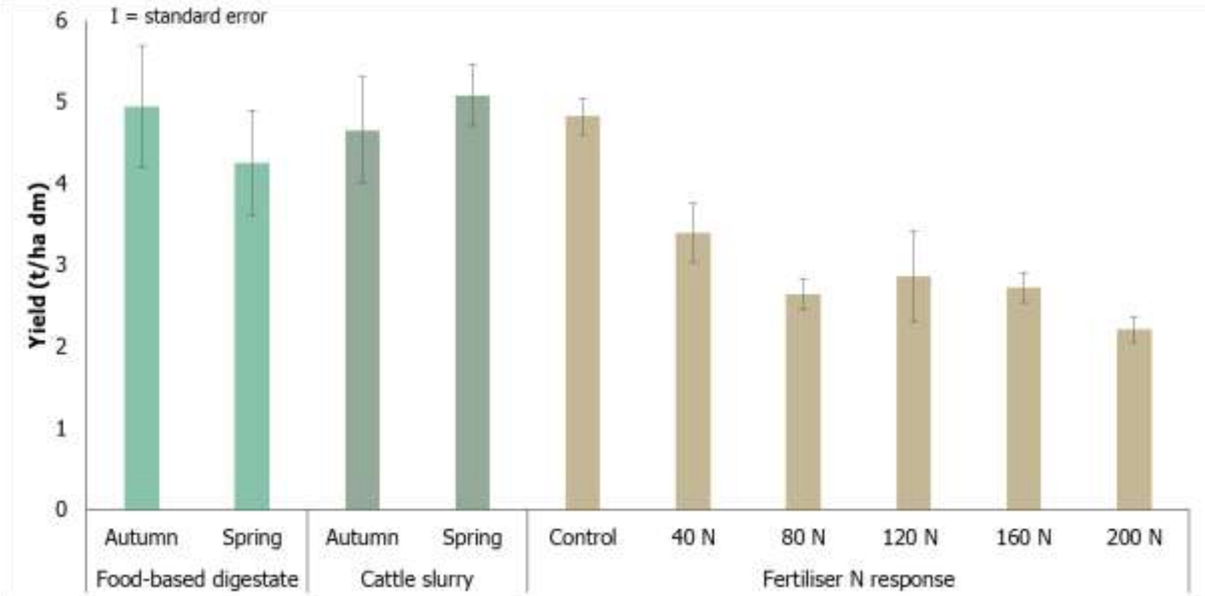

Figure 2.21. Newark grass yields (t/ha dry matter).

Site 12: North Wyke

There were no significant differences in yield following applications of food-based and manure-based digestate and cattle slurry in autumn 2011 and spring 2012 compared with the untreated control (*P*=0.50; Appendix I, Table 3). The lack of yield and N offtake response at the site was a reflection of the late harvest caused by exceptionally wet weather during May and June. Because neither grass yields nor grass N offtakes responded to fertiliser N additions, NUEs could not be calculated for this site.

Site 13: Pwllpeiran

Manufactured fertiliser N was applied on the 28 March 2012 and it was planned to apply the organic materials the next day. However, the spring organic material applications were delayed (along with the second manufactured N applications) due to wet weather until 2 May 2012, which constrained the grass yield response on these treatments.

Grass N offtakes responded to manufactured fertiliser N applications (r^2= 91%; Figure 2.22), therefore at this site organic material NUEs were calculated on an N offtake basis. The NUE of the spring applied digestates was higher (P<0.001) than the autumn applications (Figure 2.23; Appendix I, Table 3).

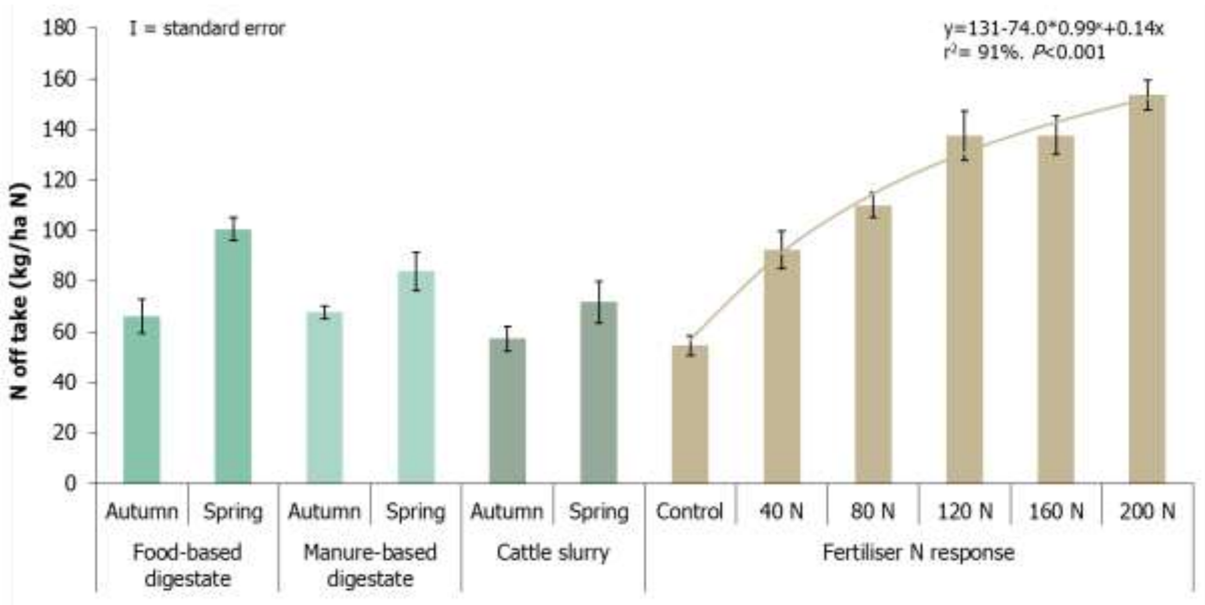

Figure 2.22. Pwllpeiran grass N offtakes (kg N/ha).

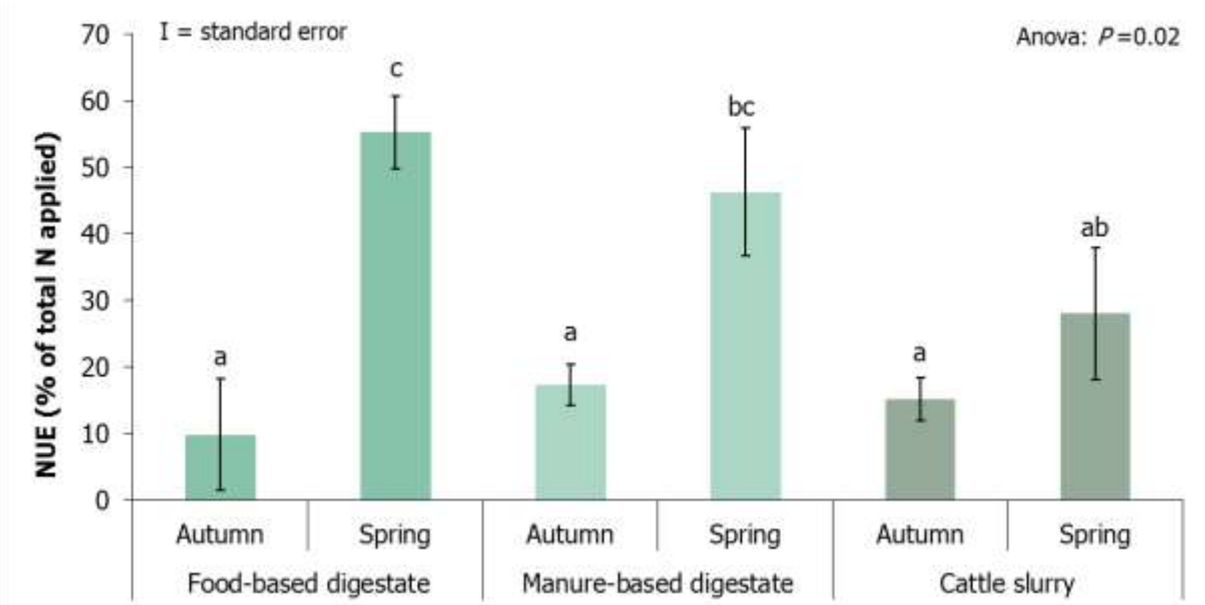

Figure 2.23. Pwllpeiran N use efficiency (% of total N applied) 'N offtake method'. *Columns labelled with different letters are significantly different (P<0.05) from each other.*

Site 14: Wensum

The application of food and manure-based digestate and pig slurry in spring 2012 increased winter wheat yields by 1.7-2.5 t/ha (*P*<0.001) compared with the untreated control (Figure 2.24; Appendix I, Table 3). In comparison, autumn 2011 applied food-based digestate and pig slurry increased (*P*<0.001) winter wheat yields by 0.6-1.5 t/ha compared to the untreated control (Figure 2.25; Appendix I, Table 3). Grain yields responded to manufactured fertiliser N applications (Figure 2.24). The NUEs were calculated using the yield method and were higher (*P*<0.05 in Duncan's test) for the spring applied treatments than for the autumn applied treatments (Figure 2.25).

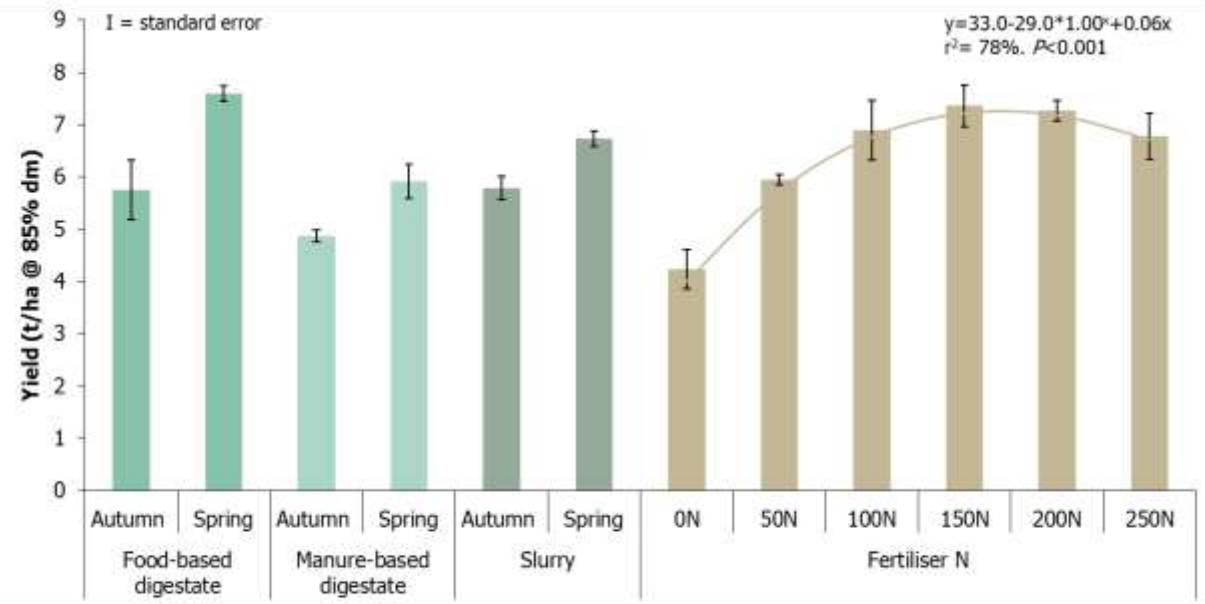

Figure 2.24. Wensum winter wheat yields (t/ha @85% dry matter).

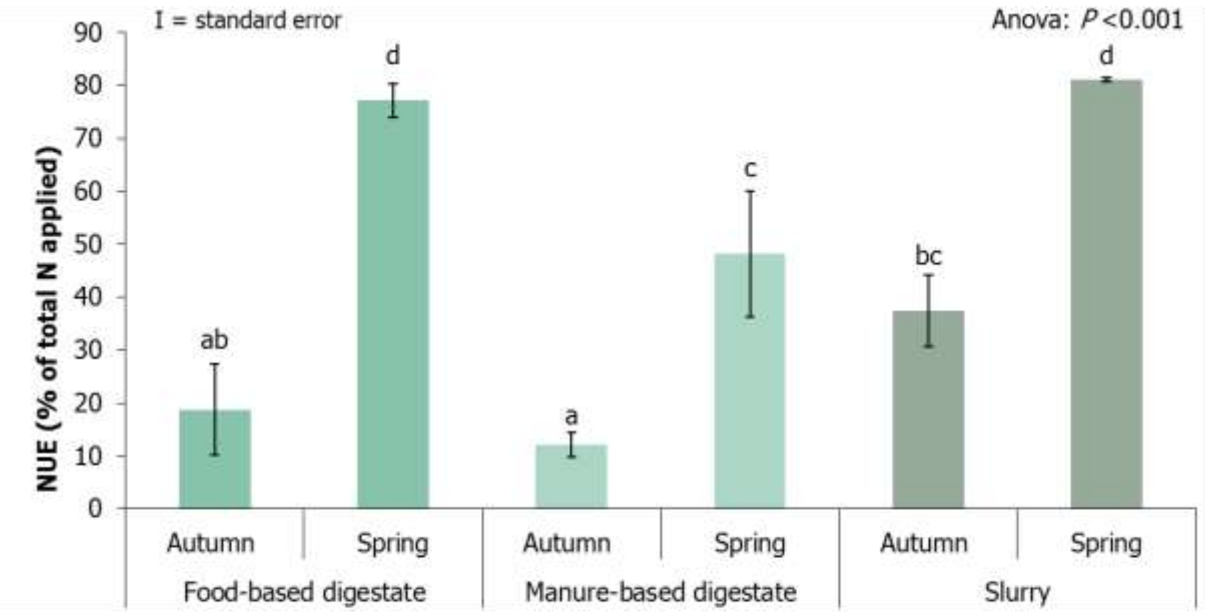

Figure 2.25. Wensum N use efficiency (% of total N applied) 'yield method'. *Columns labelled with different letters are significantly different (P<0.05) from each other.*

Site 15: Devizes

The application of food and manure-based digestate and cattle slurry in spring 2013 increased winter wheat yields by 2.0-3.2 t/ha (P<0.001) compared with the untreated control (Figure 2.26; Appendix I, Table 3). In comparison, the autumn 2012 applied food and manure-based digestate and cattle slurry treatments increased (P<0.001) grain yields by 0.5-0.8 t/ha compared with the untreated control (Figure 2.27; Appendix I, Table 3).

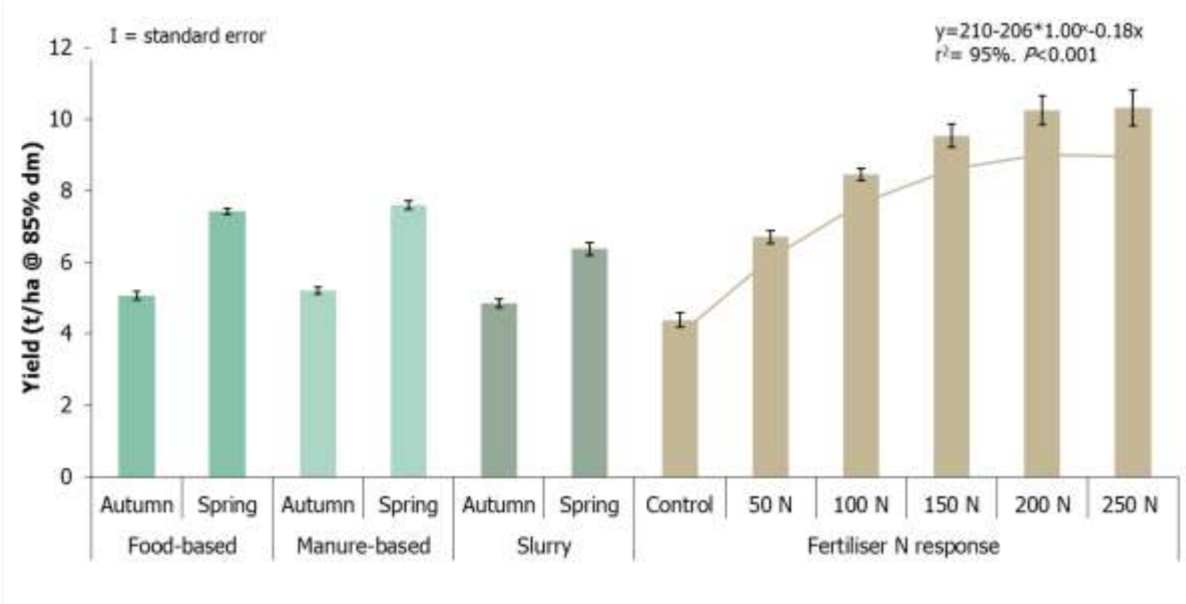

Figure 2.26. Devizes winter wheat yield (t/ha @85% dry matter).

The grain yield responded to manufactured fertiliser N applications (r^2= 95%; Figure 2.26), with NUEs calculated using the yield method. The NUE of the spring applied food and manure-based digestate and cattle slurry treatments was higher (P<0.05 in Duncan's test) than the autumn applications (Figure 2.27).

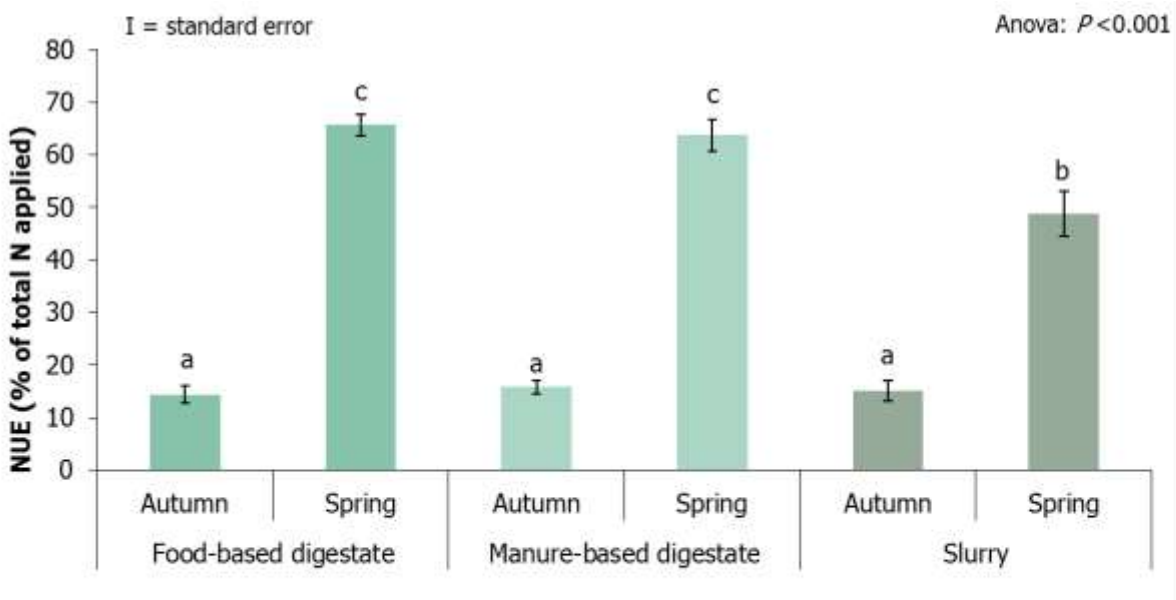

Figure 2.27. Devizes N use efficiency (% of total N applied) 'Yield method'. *Columns labelled with different letters are significantly different (p<0.05) from each other.*

2.3 Discussion

Table 2.4 summarises the NUEs obtained at each site and organic material application timing. Across all sites and timings, the food and manure based digestates had similar mean NUEs (at 37-38%), and were higher (*P*=0.02 in cross site Anova) than the livestock slurries (mean 31%) reflecting the higher RAN contents of the digestates (75% and 61% for food and manure-based digestates, respectively; Table 2.3) compared with the livestock slurries (54%; Appendix 1, Table 2). For all the organic materials, the mean NUE for the autumn application timings (13-16%) was lower (*P*<0.001 in cross site Anova) than for the spring application timings (41-54%), reflecting overwinter nitrate leaching losses from the autumn applications, and strongly suggesting that spring application timings maximise the N use efficiency of digestate (and livestock slurry) applications. However, targeted autumn applications i.e. where crops have an autumn N requirement (e.g. oilseed rape) would allow greater NUE assuming the application rate was adjusted to only supply the quantity of N required. There was also a significant (*P*<0.001) interaction between site and treatment and between site and season in the cross site analysis, most likely due to differences in both the composition of the organic materials applied at each site (Appendix 1, Table 2) and differences in agro-climatic conditions (e.g. over-winter rainfall). However, the NUE of the food-based digestate was always greater than the NUE of slurry, and spring applications were more efficient than autumn applications.

In addition to the mean crop available N figures, Table 2.4 also highlights the variability between different experimental sites. This variability is likely a result of the complex systems being represented by only fifteen experiments, including effect of soil quality/condition (e.g. soil structure, organic matter content, soil compaction), weather, digestate properties (e.g. pH, dry matter, organic matter content), differences in crop uptakes (e.g. crop type, age of sward, rooting quality) etc. It should be noted that the variability observed in these experiments is similar to that seen for all organic materials, even those with NUE data in the 'Fertiliser Manual (RB209)' (Defra, 2009) or MANNER-*NPK* (Nicholson *et al.*, 2013), where the mean data presented is based on a similarly variable dataset, again due to the complex systems and multitude of interactions being represented.

Indeed, it is partly due to these uncertainties that the 'Fertiliser Manual (RB209)' (Defra, 2010) recommends that "*manure application to supply no more than 50-60% of the total nitrogen requirement of the crop, with inorganic fertiliser used to make up the difference*". Therefore, in terms of operational recycling, the variability behind the mean figures highlights the importance of using all available information, following best practice (e.g. analyse the batch of organic material to be used, spread it as accurately and evenly as possible, account for the nutrients supplied and use organic materials in synchrony with manufactured fertilisers) and taking advice from a FACTS adviser experienced in the use of organic materials.

The measured NUE values for the food-based and manure-based digestates were compared with MANNER-*NPK* (Nicholson *et al.*, 2013) predictions of crop available N supply (Figure 2.28), with the intercept of the regression set at zero (i.e. when MANNER-NPK predicts zero NUE, the actual NUE was assumed to be zero too). MANNER-*NPK* predictions compared well with the measured values (i.e. the slope of the regression lines was 0.92), with 57% of the variation accounted for, which given the level of variability outlined above is very encouraging, albeit with a lower correlation than the calibration data used for MANNER-*NPK* validation. Figure 2.29 shows that there was a slight improvement in the correlation for the manure-based digestates (slope of regression line = 0.95) compared to the food-based digestates (slope of regression line = 0.89) which is not surprising as MANNER-*NPK* was developed using research data on N losses (i.e. nitrate leaching, ammonia volatilisation, N_2O/N_2 emissions) and crop N uptake from experiments where livestock manures had been applied, rather than on data relating to digestates *per se*.

Table 2.4. Summary of calculated NUEs at each of the digestate N response sites.

Site		Cross-compliance soil group	Crop	Application timing	Food-based digestate	Manure-based digestate	Live-stock slurry
1	Aberaeron	Medium	G	Autumn Spring	36.3 53.7	- -	39.3 55.1
2	Aberdeen	Sandy/light	SB	Pre-drilling Post-drilling	80.5 46.4	55.5 43.3	58.6 14.7
3	Ayr*	Medium	G	Autumn Spring	- -	- -	- -
4	Beith	Medium	G	Autumn Spring	2.3 45.7	- -	7.3 47.1
5	Brawdy	Medium	WW	Autumn Spring	1.6 38.5	0.8 16.6	4.9 34.1
6	East Malling	Medium	WW	Autumn Spring	5.3 17.2	13.1 45.9	4.4 10.4
7	Gleadthorpe	Sandy/light	POTS	Early spring Late spring	56.5 72.0	58.5 68.1	44.3 49.3
8	Harper Adams*	Medium	SB	Early spring Late spring	- -	- -	- -
9	Loddington	Heavy	WW	Autumn Spring	8.6 35.7	9.8 22.9	3.6 19.2
10	Morpeth	Medium	G	Autumn Spring	24.4 60.5	34.8 95.9	22.4 39.4
11	Newark*	Medium	G	Autumn Spring	-	-	-
12	North Wyke*	Heavy	G	Autumn Spring	- -	- -	- -
13	Pwllpeiran**	Medium (heavy)	G	Autumn Spring	9.9 55.3	17.4 46.3	15.3 28.1
14	Wensum DTC	Sandy/light	WB	Autumn Spring	18.8 74.0	12.2 48.2	37.5 81.1
15	Devizes (Hampshire/Avon DTC)	Chalk/limestone	WW	Autumn Spring	14.4 65.7	15.8 63.7	15.1 48.8
Overall mean (±CI)					**37 (±7)**	**38 (±7)**	**31 (±6)**
Mean autumn (±CI)					**13 (±4)**	**15 (±6)**	**16 (±6)**
Mean spring (±CI)					**54 (±7)**	**52 (±8)**	**41 (±7)**

CI = 95% Confidence Interval
*NUEs could not be calculated at Ayr, Harper Adams, Newark and North Wyke (see text for details)
**NUEs were based on grass N offtake at Pwllpeiran.

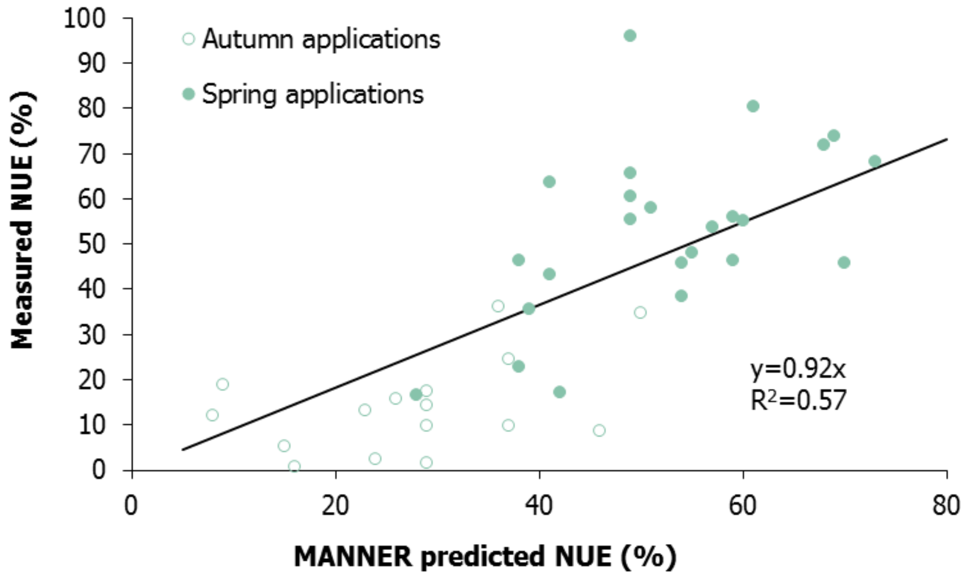

Figure 2.28. Comparison of MANNER predicted and measured NUE values for food- and manure-based digestates, showing autumn (n=16) and spring (n=24) application timings.

a) b)

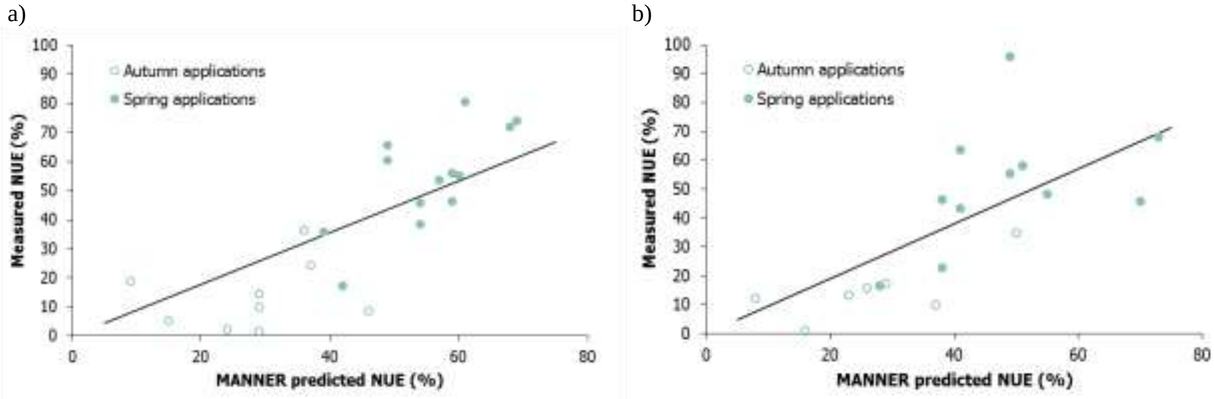

Figure 2.29. Comparison of MANNER predicted and measured NUE values for a) food-based digestates (n=22) and b) manure-based digestates (n=18).

Despite the encouraging performance of the MANNER-*NPK* tool, predictions for digestates could be further improved by incorporating data gathered in the course of this project (see WP2.2) to tailor the nitrate leaching, and ammonia and N_2O emission algorithms within the MANNER-*NPK* calculation engine as well as investigating a possible under estimation of spring NUE and over estimation of autumn NUEs.

2.4 Conclusions

The overall nitrogen use efficiency (NUE) of the organic materials applied (via bandspreading) to agricultural land was related to their readily available (RAN) content. The food and manure-based digestates had similar NUEs (37-38%), which was higher than the mean NUE of 31% measured for livestock slurries. The NUE from the spring digestate applications (mean 52-54%) was considerably higher than from the autumn applications (mean 13-15%), because of over-winter nitrate leaching losses from the autumn applications. These results strongly suggest that farmers should be advised, where practically possible, to apply digestates to crops with an N demand, commonly in the spring/summer and only in the autumn to crops which are actively growing (e.g. oilseed rape and grass) with application rates controlled to match the crop N requirement.

There was good agreement between MANNER-*NPK* estimates of NUE and the field measurements, albeit with some variability which is common in datasets of this kind due to the complex systems and multitude of interactions being represented. MANNER-*NPK* can therefore provide good estimates for farmers and advisors who want to account for the nutrient content of food-based and manure-based digestates when developing fertiliser strategies. However, there is scope for the MANNER-*NPK* estimates to be further improved by incorporating information on environmental N losses from digestates (derived as part of Work Package 2.2, see Section 3) into the MANNER-*NPK* calculation algorithms.

The data on digestate nutrient analysis and NUEs obtained in this work package will contribute to the evidence base for future revisions of RB209, SRUC Technical Notes and PLANET, so that these tools can continue to provide up-to-date and robust advice for farmers and land managers.

3. WP2.2 Effects of digestate and compost applications on nitrous oxide and ammonia emissions to air, and leaching losses to water

3.1 Methodology

3.1.1 Experimental sites

Three sites (North Wyke, Pwllpeiran and Wensum) were established on a range of soil types and agroclimatic areas in autumn 2010 (see Figure 2.2 and Table 2.1 in Section 2). The soil at each site was characterised as described in Section 2. Topsoil bulk density and available water capacity was also measured at these sites using standard methods (Anon, 1982).

3.1.2 Treatments and design

Treatments comprised of a range of organic materials (Table 3.1). At Wensum, where leaching losses to water were quantified, these were applied in the autumn, and then repeated in the spring to new experimental plots. At North Wyke and Pwllpeiran, only spring applications were evaluated. At each experimental site, there were also plots receiving manufactured fertiliser N as part of the WP2.1 treatments (Table 2.2). For practical reasons, the spring, autumn and manufactured fertiliser N treatments were grouped separately (with each group of plots having an untreated control). Within each group, each treatment was replicated three times and arranged in a randomised block design. Plot sizes were 3-7 m wide by 8-15m long; the organic material plots were orientated at 20 degrees to the 'vertical' to allow for correct placement of the wind tunnels for measuring ammonia emissions.

Table 3.1 Organic material treatment details.

Treatment No	Treatment details
1	Untreated control
2	Slurry surface broadcast (incorporated within 24 hours in autumn)
3	Livestock slurry bandspread
4	Farmyard manure
5	Food-based digestate surface broadcast (incorporated within 24 hours in autumn)
6	Food-based digestate bandspread
7	Green or green/food compost

Organic material treatments were applied in autumn 2011 at Wensum and in spring 2012 at all sites. Cattle FYM and slurries were used at North Wyke and Pwllpeiran, and pig FYM and slurry at Wensum, obtained from sources local to each site. The green (Pwllpeiran and North Wyke) or green/food (Wensum) compost and food and manure-based digestates were sourced from BSI PAS100/PAS110 accredited suppliers (or suppliers working towards accreditation) local to the experimental sites. The liquid materials (livestock slurry and digestate) were applied using the ADAS small plot applicator (Plate 3.1) and the solid materials (FYM and compost) were applied to the plots by hand (at the North Wyke site the liquid organic materials were also applied by hand). At the grassland sites, the liquid material applications were by trailing shoe with the spacing between the bands set at 20cm. At Wensum, the applications were by trailing hose with the spacing between the bands set at 30cm, so as to be representative of commercial practice. At Wensum, the autumn applied broadcast pig slurry and digestates were incorporated into the soil within 24 hours of application, using a rotavator to comply with NVZ rules. As stated previously, the three sites were part of a wider Defra project (AC0116) investigating environmental emissions following a wide range of livestock manures (e.g. poultry manures, livestock slurry, farmyard manures), therefore these additional treatments were included in the wider experimental design.

The amount of organic material applied to each plot was weighed and recorded, so that the application rate to each plot could be accurately determined. Target application rates were in the range 120-250 kg/ha total N to comply with the requirements of the NVZs Action Programme (*i.e.* the organic manure N field-limit of 250 kg/ha total N) (SI, 2008; WSI, 2008).

Plate 3.1. Plot application equipment for digestate and slurry.

3.1.3 Crop management

The grass (at North Wyke and Pwllpeiran) and winter wheat (at Wensum) were grown according to best farm practice, with crop protection products applied as needed and according to good agricultural practice to control weeds, pests and diseases. All treatments had manufactured fertilisers (P_2O_5, K_2O & SO_3) applied based on the requirements of the untreated control (Defra, 2010b) to ensure that only N limited plant growth. All recommendations were checked by a FACTS qualified adviser.

3.1.4 Organic material analysis

At each site and application timing, a representative sample of each organic material type from each replicate block of plots was taken at spreading (*c.*2 litres per block for each liquid organic material and *c.*2 kg per block for each solid organic material) and analysed for dry matter, pH, total N, ammonium-N and nitrate-N using standard methodologies (MAFF, 1986).

3.1.5 Ammonia emissions

Wind tunnels were used to assess ammonia emissions from the livestock manure treatments at each site, based on the design developed by Lockyer (1984). Each wind tunnel consisted of two parts; a transparent polycarbonate canopy (2.0 m x 0.5 m) which covered the plot area, and a stainless steel duct housing a fan which drew air through the canopy at a speed of 1 m/s; an anemometer measuring the wind speed, which was recorded using a pulse counter. A sub-sample of the air entering and leaving the tunnel was drawn through absorption flasks containing 80 ml of 0.02 M orthophosphoric acid. The absorption flasks were changed after 24 hours and then daily for between 7 (digestate, compost, livestock slurries and FYM) and 21 days (poultry manures only). The loss of ammonia from beneath each tunnel was calculated as the product of air flow through the tunnel and the difference between the concentrations of ammonia in the air entering (i.e. the background ammonia concentration) and leaving the tunnel as follows:

$$\text{Ammonia loss} = ((b/a)_{\text{outlet bubbler}} - (b/a)_{\text{inlet bubbler}}) * c$$

where,

a = volume of air sampled by each acid trap,
b = quantity of ammonia-N in each trap over the sampling period,
c = volume of air drawn through each tunnel.

The rate of loss was calculated over each time period so that the pattern of loss could be quantified and cumulative losses were then calculated by summing over all sampling periods.

3.1.6 Greenhouse gas emissions

Nitrous oxide (N_2O), methane (CH_4) and carbon dioxide (CO_2) emissions were measured using the static chamber technique (Clayton *et al.* 1994), from three replicate plots per treatment, using 5 chambers per plot (giving a total of 15 replicate chambers per treatment). Each chamber had dimensions of 40 cm x 40 cm square and was 25 cm tall, giving a soil surface area coverage of 0.16 m^2. The chambers were installed immediately after manure application and positioned in a 5 cm deep slot cut in the soil. The chambers were designed to completely enclose growing arable crops and grassland, without damage, with chamber extensions fitted to enable measurements to be taken from mature cereal and grass crops. On each sampling occasion, the chambers were covered for at least 40 minutes before the headspace was sampled. Sampling was normally conducted between 10 am and 4 pm, as previous studies have shown that emissions at this time of day approximate to average diurnal emission rate. The samples were transferred to evacuated vials prior to Gas Chromatography analysis (using an Electron Capture Detector –ECD for N_2O and a Flame Ionisation Detector – FID for CH_4 and CO_2). To verify the assumption of linear gas accumulation within a chamber's headspace, one chamber was selected on each sampling occasion from which a time series of headspace samples was taken every 15 minutes up to 60 minutes after closure. The following steps were taken to help ensure that linearity in gas accumulation was achieved, by (i) ensuring an air-tight seal between the chamber and soil; (ii) ensuring an air-tight seal between the chamber and lid; (iii) using 'large' chambers to provide as much headspace as practically possible, whilst retaining analytical sensitivity.

Data from previous studies have indicated that *c.*75% of total *direct* N_2O emissions are likely to occur in the first 4-6 weeks following application. Therefore the sampling strategy (Table 3.2) was weighted accordingly, with *c.*50% of sampling events carried out during the (likely) period of highest N_2O fluxes (i.e. 4-6 weeks after application), giving a total of at least 30 measurements over a 12 month period.

Table 3.2 Nitrous oxide sampling strategy following treatment application.

Weeks after application	Number of measurements
One week before	1
0-2	10
2-4	4
4-8	2
8-12	2
12-16	2
16-20	2
20-24	2
24-28	1
28-32	1
32-36	1
36-40	1
40-44	1
44-48	1
48-52	1
Total	**32**

3.1.7 Leaching losses

At the Wensum site, leaching losses to water were measured from the plots receiving autumn applications of organic materials, using Teflon cup water samplers. Five porous cups were installed on each plot to a depth of 90 cm. Samples of soil water were collected every 2 weeks or after 50 mm drainage, whichever occurred sooner, throughout the drainage period and analysed for nitrate and ammonium-N, soluble P and *E.coli*, using standard methodologies (Anon, 1986). Drainage estimates were obtained using IRRIGUIDE (Bailey and Spackman, 1996) and were combined with the pollutant concentration data to calculate losses in drainage water.

3.1.8 Harvest

Crop yields were measured at Wensum using a small plot combine. At Pwllpeiran and North Wyke grass yields were measured at first cut using a mechanical grass harvester. Samples of grain and cut grass were analysed for N, P, K, Mg, S and dry matter content (Anon, 1986).

3.1.9 Other measurements

Soil samples for mineral nitrogen (SMN) determination were taken periodically (from 0-10 cm depth as this is where the main N_2O fluxes arise from) throughout the experimental period to quantify changes in soil N supply following the organic material applications. Soil moisture content measurements on a block by block basis were also made on each GHG sampling occasion. Daily rainfall and mean air and soil temperature (at 5cm depth) data were measured at each site or obtained from a nearby meteorological station.

3.1.10 Statistical analysis

At each experimental site, conventional analysis of variance (ANOVA) comparisons were undertaken between the different treatments in terms of nitrous oxide and ammonia emissions to air, and nitrate, phosphorus and microbial pathogen losses to water, with comparison of P statistics (quoted in the text). A separate ANOVA was carried out at each site, after which *post-hoc* testing was undertaken to evaluate which treatment means were different from each other using a Duncan's multiple range test (using Genstat version 12; VSN International Ltd, 2010). This test assigns different letters to treatment values which are significantly different from each other at the 5% level ($P<0.05$). In the tables of results and graphs, treatments which are statistically significantly different (at $P<0.05$) are marked with different letters. For example, if the food-based digestate treatment result is marked with 'a' and the cattle slurry treatment result with 'b', then these two treatments are different from each other. However, if the manure-based digestate treatment result was marked with 'ab', then it is not different from either the food-based digestate or the cattle slurry treatment results.

Additionally, the pooled data were analysed to assess effects of nitrous oxide and ammonia emissions to air (*i.e.* a cross-site analysis ANOVA was undertaken). This enabled us to assess whether a particular treatment had had a statistically significant effect at each site, and across *all* study sites. The ANOVA also indicated if there were significant interactions between sites and treatments *i.e.* if the effect of a treatment varied across the sites.

3.2 Results and Discussion

3.2.1 Manure analysis

The composition, application rate and N loading of the organic materials applied at each site and timing are shown in Table 3.3 (Wensum) and 3.4 (North Wyke and Pwllpeiran). As expected the food-based digestate had higher total N contents (mean 7.0 kg/t, across all 3 sites) than the pig slurry (mean 2.8 kg/t, at Wensum) or cattle slurry (mean 2.4 kg/t, across two sites). The readily available N (RAN) contents of the food-based digestate and pig slurry (mean 79% and 81% of total N, respectively) were higher than the cattle slurry (mean 55% of total N).

Table 3.3 Organic material analyses and application rates in autumn 2011 and spring 2012 at Wensum.

Determinands (kg/t fw[1] except where stated)	Autumn 2011				Spring 2012			
	Food-based digestate	Pig slurry	Pig FYM	Green/ food compost	Food-based digestate	Pig slurry	Pig FYM	Green/ food compost
Dry matter (%)	5.4	2.3	24	54	4.4	2.7	23	48
Total N	7.8	3.0	8.1	11	6.9	2.6	9.2	9
Ammonium-N	6.3	2.2	0.8	1.5	6.2	2.2	0.2	0.2
Nitrate-N	< 0.01	< 0.01	0.1	< 0.01	< 0.01	< 0.01	0.6	< 0.01
RAN	6.3	2.2	0.9	1.5	6.2	2.2	0.8	0.2
(% total N)	*82*	*75*	*9*	*14*	*89*	*86*	*3*	*2*
pH	8.8	7.5	8.4	7.0	8.7	8.0	7.4	8.3
Application rate (t or m^3/ha)	32	41	30	20	30	38	30	20
N applied (kg/ha)	245	122	244	216	207	98	277	181
RAN applied (kg/ha)	201	92	23	30	185	85	7	4.5

[1] kg/t fw = kilograms/tonne fresh weight

Table 3.4 Organic material analyses and application rates in spring 2012 at North Wyke and Pwllpeiran.

Determinands (kg/t fw[1] except where stated)	North Wyke				Pwllpeiran			
	Food-based digestate	Cattle slurry	Cattle FYM	Green compost	Food-based digestate	Cattle slurry	Cattle FYM	Green compost
Dry matter (%)	5.1	6.1	20	60	6.1	4.9	24	51
Total N	8.0	2.6	5.8	13.5	5.4	2.2	4.9	7.0
Ammonium N	5.8	1.4	< 0.01	0.7	3.9	1.2	< 0.01	0.1
Nitrate N	< 0.01	< 0.01	0.3	< 0.01	< 0.01	< 0.01	0.4	< 0.01
RAN	5.8	1.4	0.3	0.7	3.9	1.2	0.4	0.1
(% total N)	*73*	*56*	*0.3*	*5*	*72*	*53*	*8*	*1*
pH	8.1	8.2	9.0	8.5	8.4	7.0	7.3	7.9
Application rate (t or m^3/ha)	20	30	25	20	20	30	25	20
N applied (kg/ha)	160	78	144	271	107	67	122	140
RAN applied (kg/ha)	117	43	0.4	15	76	35	10	1

1 kg/t fw = kilograms/tonne fresh weight

3.2.2 Ammonia emissions - results

North Wyke

Ammonia emissions from the spring 2012 organic material applications at North Wyke were similar from the food-based digestate and cattle slurry, and both these treatments had higher emissions than green compost and cattle FYM (P<0.05; Figure 3.1). Perhaps surprisingly, there were no differences (P>0.05) in ammonia emissions between the bandspread and broadcast food-based digestate and cattle slurry treatments.

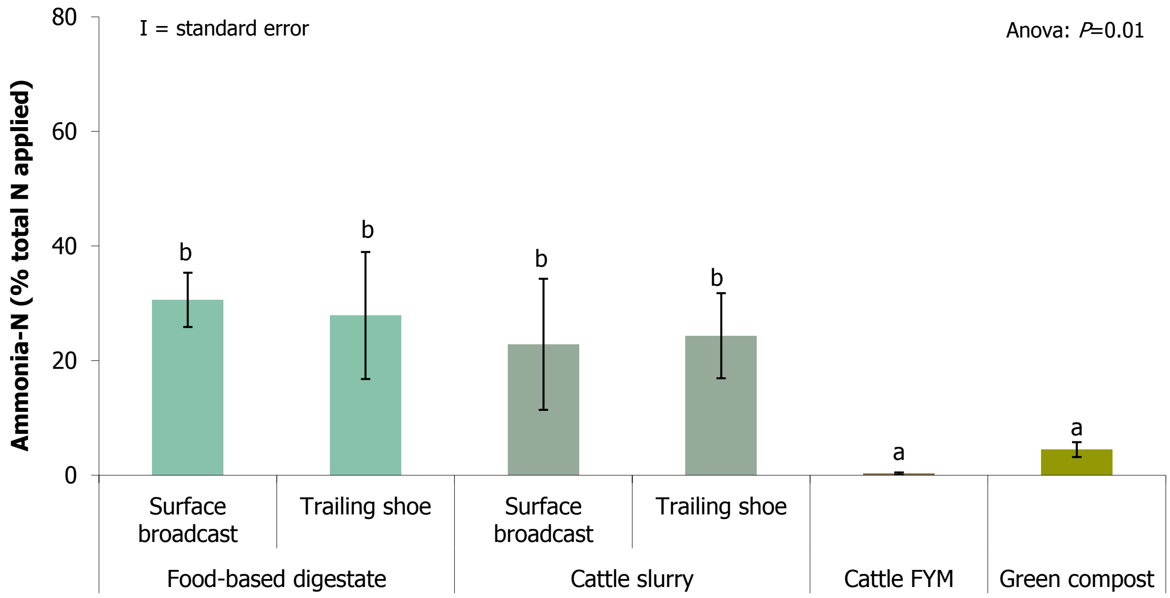

Figure 3.1. Ammonia emissions at North Wyke (spring 2012). *Columns labelled with different letters are significantly (P<0.05) different from each other.*

Pwllpeiran

Ammonia emissions following the spring 2012 organic material applications at Pwllpeiran were higher from food-based digestate than from cattle slurry, with the green compost and cattle FYM treatments having the lowest emissions (*P*<0.05; Figure 3.2). Notably, bandspreading significantly reduced (*P*<0.05) ammonia emissions from the food-based digestate by *c.25%* and cattle slurry by 70% compared with the respective broadcast applications.

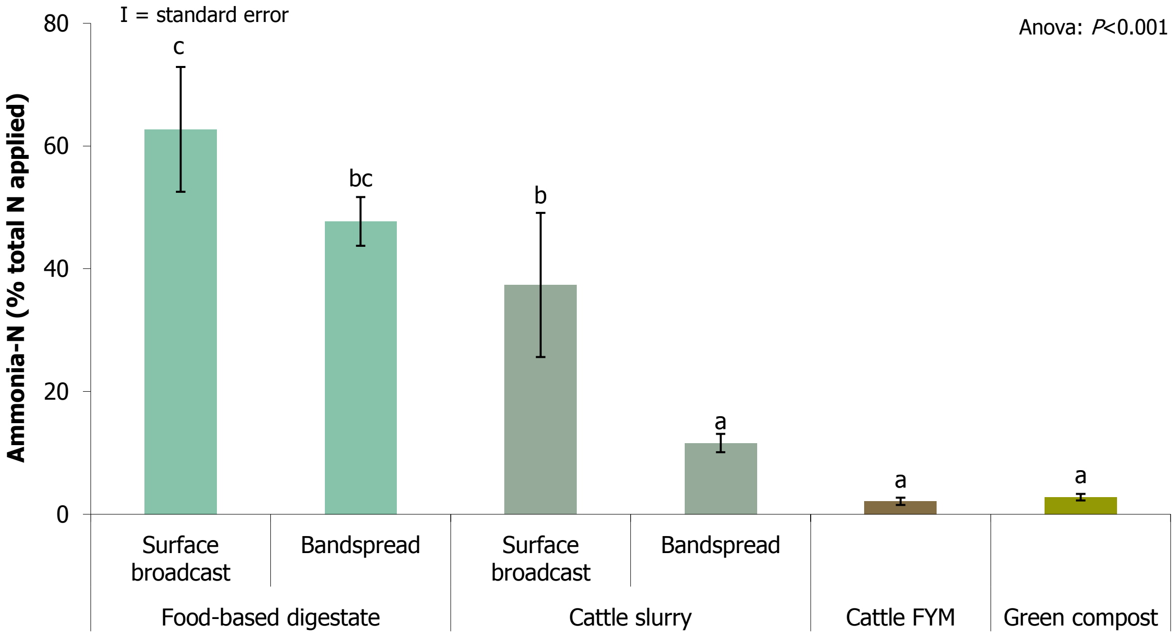

Figure 3.2. Ammonia emissions (% of total N applied) following the spring 2012 organic material applications at Pwllpeiran. *Columns labelled with different letters are significantly (P<0.05) different from each other.*

Wensum

At Wensum, ammonia emissions following the autumn 2011 (31st August) organic material applications were again greater from food-based digestate than from pig slurry, with the pig FYM and green/food compost having the lowest emissions (*P*<0.05; Figure 3.3). As both the food-based digestate and pig slurry had similar RAN contents (*c.*80% of total N), the greater ammonia emissions from the food-based digestates were probably related to their higher pH (8.8 for food-based digestate and 7.5 for pig slurry).

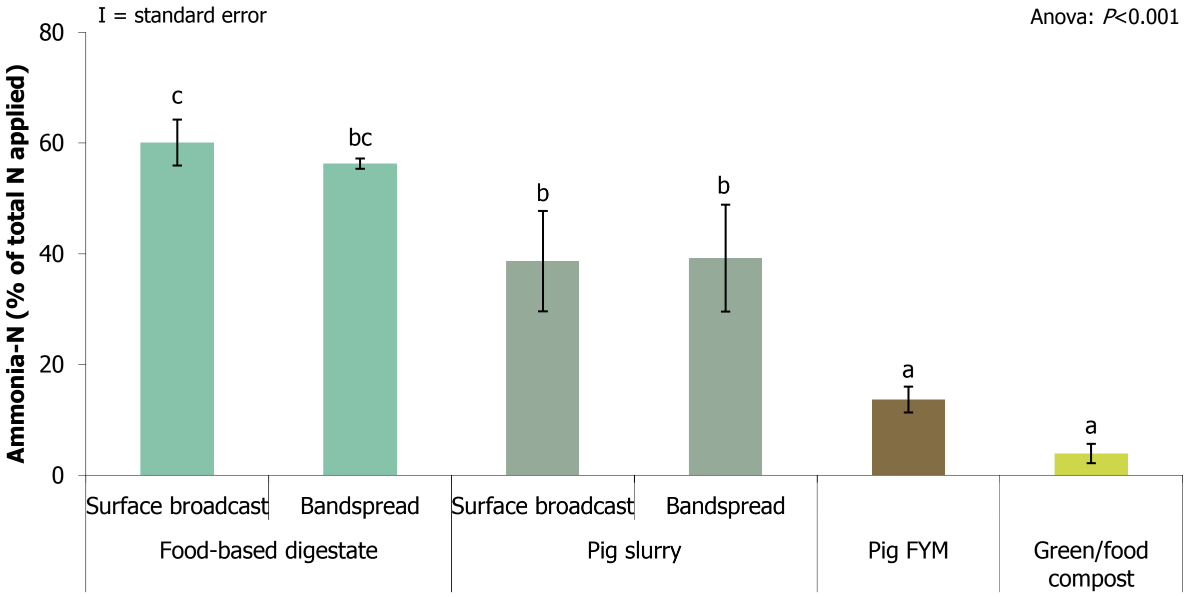

Figure 3.3. Ammonia emissions (% of total N applied) following the autumn 2011 organic material applications at Wensum. *Columns labelled with different letters are significantly (P<0.05) different from each other.*

There were no significant differences in ammonia emissions between the bandspread and broadcast (soil incorporation within 24 hours) food-based digestate and pig slurry applications. This may be because the broadcast materials were incorporated into the soil within 24 hours (in accordance with Nitrate Vulnerable Zone Regulations), which would have reduced the ammonia emissions from these treatments.

Ammonia emissions were lower following spring 2012 food-based digestate and pig slurry treatments than in autumn. In the autumn, the slurry and digestate remained on the soil surface and did not infiltrate into the soil, whereas in the spring there was more rapid soil infiltration and hence lower ammonia emissions. Ammonia emissions were similar from the food-based digestate and pig slurry treatments, with the pig FYM and green/food compost again having the lowest emissions ($P<0.05$; Figure 3.4). There were no significant differences between the bandspread and broadcast food-based digestate and pig slurry treatments, which was most probably due to the bandspread applications not staying in a band (plus some temporary ponding on the soil surface), followed by 'rapid' infiltration into the soil.

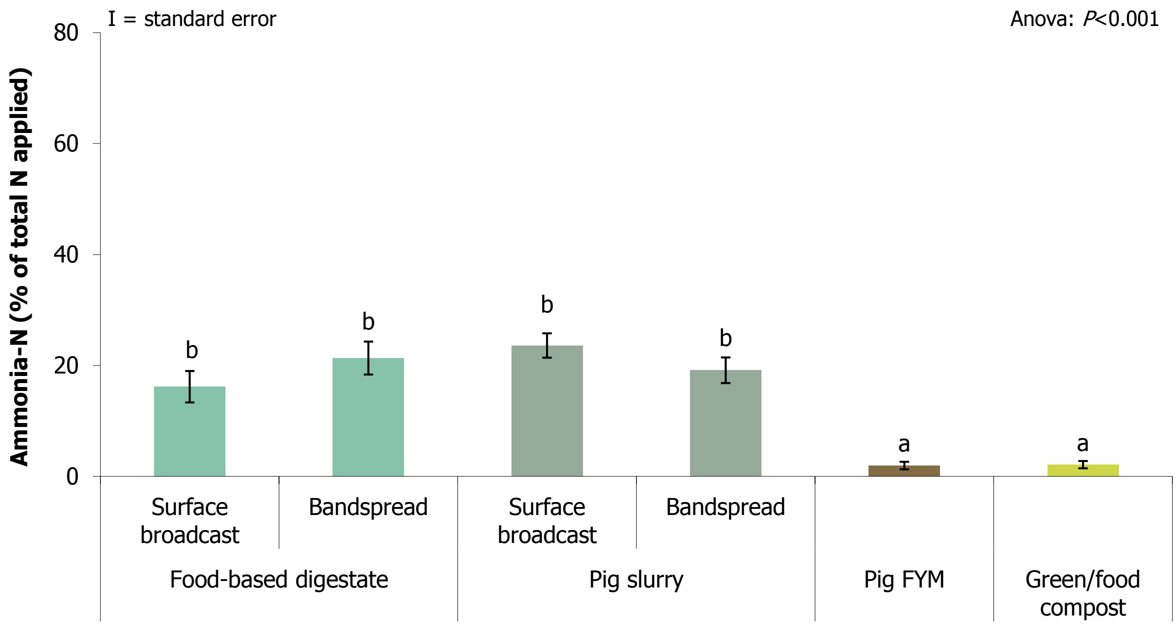

Figure 3.4. Ammonia emissions (% of total N applied) following the spring 2012 organic material application at Wensum. *Columns labelled with different letters are significantly (P<0.05) different from each other.*

3.2.3 Ammonia emissions - discussion

The cross-site analysis of the ammonia emissions data from the autumn 2011 applications at Wensum, and the spring 2012 organic material applications at North Wyke, Pwllpeiran and Wensum is summarised in Figure 3.5. Ammonia emissions were similar on the broadcast and bandspread food-based digestate and were greater than those from the broadcast and bandspread livestock slurry, with FYM and compost having the lowest emissions. There was no difference in emissions due to spreading method for the food-based digestate, but broadcast slurry gave rise to greater emissions than band-spread slurry.

The higher ammonia emissions from the food-based digestate than from livestock slurry (P<0.05) were most probably due to the greater ammonium-N content of the food-based digestate (mean 5.6 kg/t) compared with the livestock slurries (mean 2.2 kg/t for pig slurry and 1.3 kg/t for cattle slurry). Additionally, the mean pH of the food-based digestate was 8.5 compared with 7.8 for pig slurry and 7.6 for cattle slurry. It is known that pH values greater than 8 are particularly conducive to elevated ammonia emissions from digestates (e.g. Hoeksma *et al*., 2012); indeed, acidification has been adopted as the Best Available Technology (BAT) for reducing ammonia losses from livestock slurry in some European countries (e.g. Denmark; Kai *et al*., 2008). Further research into the costs, practicalities and effectiveness of acidification of digestates (i.e. decreasing the pH) as a method of controlling ammonia emissions is required, drawing on the experience of other European countries.

Overall, bandspreading was effective at reducing ammonia emissions from livestock slurry, but not from food-based digestate. .Bandspreading of liquid organic materials (such as food-based digestate) is now a common practice, with the majority of contractor-spread digestate applied using bandspreaders. In this study, the failure to observe a reduction in ammonia emissions when bandspreading food-based digestate (in comparison with broadcast applications) was most probably due to soil and/or organic material properties that meant that the digestate did not rapidly infiltrate into the soil or did not stay in a narrow band on the soil surface. Dry matter content is known to affect ammonia emissions from cattle slurry, with emissions increasing as slurry dry matter content increases (e.g. Sogaard *et al.*, 2002; Misselbrook *et al.*, 2004); it is likely that this relationship will also hold for food-based digestates, although we do not know of any research data specific to digestates.

It is important to bear in mind that bandspreading technologies provide numerous other advantages over broadcast applications (e.g. more even digestate application and hence more accurate assessment of application rates, the ability to apply from tramlines, reduced crop damage and a cleaner sward) implying that it is still the best application method available.

The cross-site ammonia emission curves (Figure 3.6) indicate that ammonia was emitted from both the broadcast food-based digestate and livestock slurry treatments more rapidly than from the bandspread applications; this was most likely a result of the broadcast applications covering the entire crop surface area (larger surface area), whereas the bandspread applications (generally) stayed in bands and occupied a smaller surface area. The majority of the ammonia losses occurred within 6 hours of spreading highlighting the importance of rapid soil incorporation as a method for preventing N losses via this pathway.

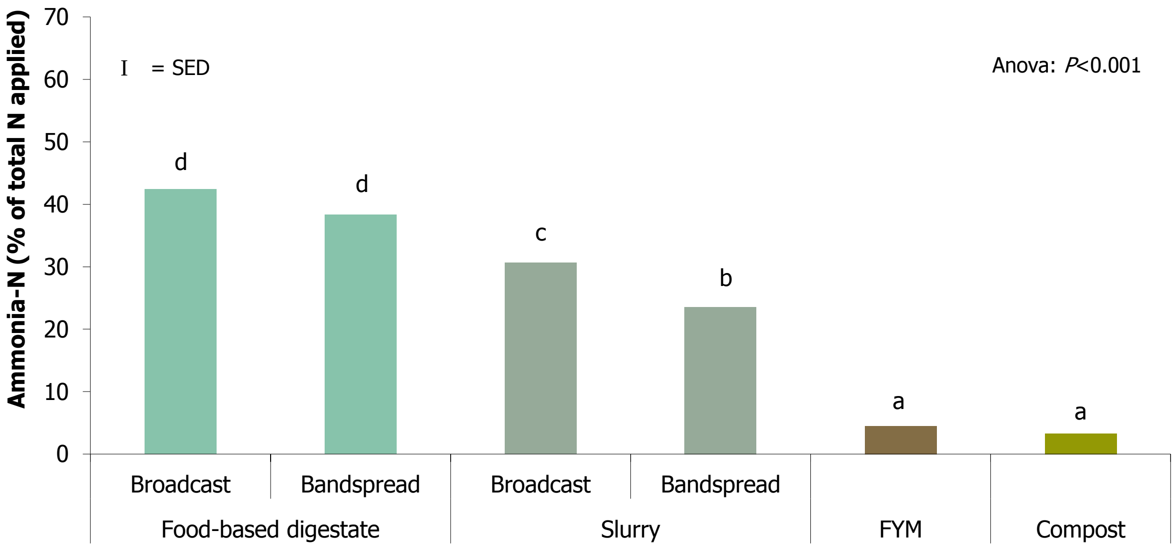

Figure 3.5. Cross-site ammonia emissions data (summary of experimental measurements) *Columns labelled with different letters are significantly (P<0.05) different from each other. SED = standard error of differences of means*

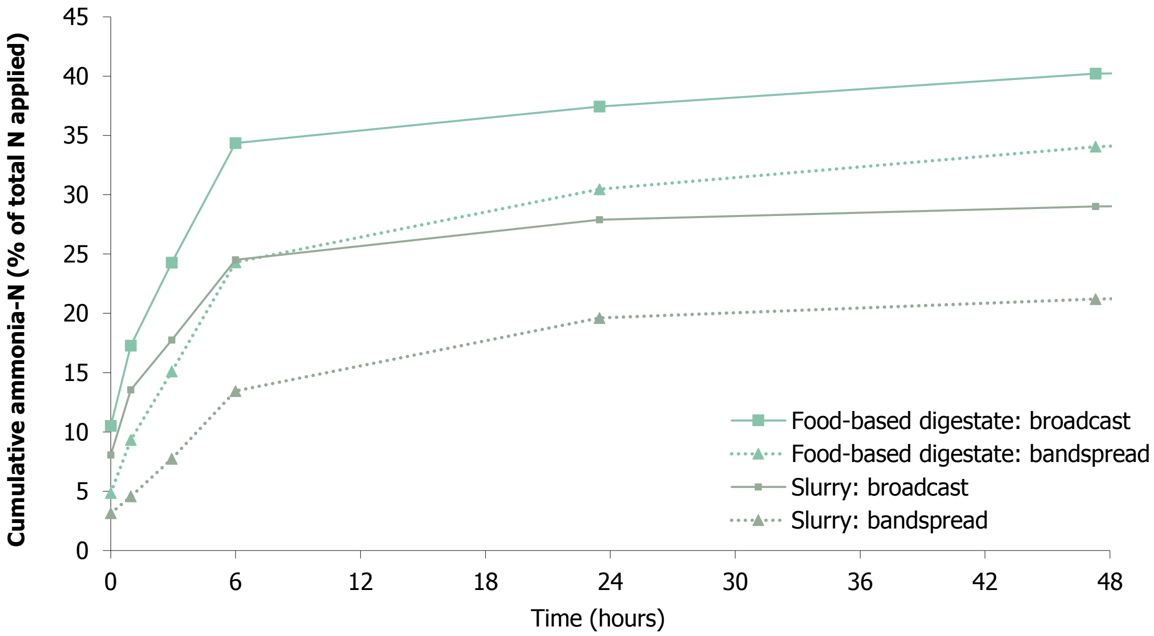

Figure 3.6. Cross-site ammonia emissions curves (harvest year 2012).

In addition to representing the loss of a valuable resource, ammonia emissions from digestate applications present a challenge to the UK meeting EU directives on ammonia emissions. Under the EU National Emissions Ceiling Directive, the UK has a proposed target to reduce ammonia emissions by 8% (relative to a 2005 baseline) between 2020 and 2029, and by 21% from 2030. The UK Ammonia Emissions Inventory (UKAEI) does not currently include emissions following the application of food-based digestate (or crop-based digestate) to agricultural land. Based on the emissions measured in this study and the estimated 1.4 million m^3 of food-based digestate currently applied to agricultural land (WRAP, 2014) at an average total N content of 5 kg/m^3, this implies that food-based digestate will add an additional 3.5 kt of ammonia, equivalent to 1% of the UK emission target (297 kt for 2010). If this is scaled up to the predicted 2020 food-based digestate volumes (5 million m^3) then food-based digestate would emit an additional 12 kt of ammonia or 4% of the UK 2010 target.

3.2.4 Nitrous oxide emissions

North Wyke

Nitrous oxide fluxes at North Wyke in spring 2012 were generally low throughout the measurement period at <20 g N_2O-N/ha/day on all treatments (Figure 3.7a). There was a small peak in emissions (*c.*30 g N_2O-N/ha/day) at the end of May which may have been related to elevated temperatures and high rainfall at this time (see Appendix II, Figures 1 and 2). Cumulative N_2O losses (net of the control) were all low (<0.5 kg N_2O/ha) and total emissions (expressed as an emission factor – EF) were all much less than the IPCC default value of 1% of total N applied (Figure 3.7b). There were no significant differences in EFs between the different treatments.

Pwllpeiran

At Pwllpeiran in spring 2012, N_2O fluxes were generally higher than at North Wyke. Emissions peaked (particularly on the FYM treatment at *c.*110 g N_2O-N/ha/day) around 2 weeks after the organic materials were applied in early May; after this, emissions on all the organic material treatments returned to background levels (*c.*10 g N_2O-N/ha/day; Figure 3.8a). As at North Wyke, cumulative N_2O losses (net of the control) were all low (<0.5 kg N_2O/ha) and EFs for all the organic materials were all less than the IPCC default value of 1% of total N applied, although the variability associated with emissions from the bandspread cattle slurry treatment suggests that the IPCC value could be exceeded on some occasions (Figure 3.8b). Emissions from the green compost were significantly lower than from the cattle slurry and FYM treatments ($P<0.05$). Although bandspreading significantly increased the EF from cattle slurry compared with surface broadcasting ($P<0.05$), there was no difference in the EF between the broadcast and bandspread digestates. However, the bandspread digestate had a significantly ($P<0.05$) lower EF than the bandspread cattle slurry.

Wensum

Nitrous oxide fluxes at Wensum in autumn peaked at *c.*100 g N_2O-N/ha/day, shortly after the organic materials were applied in early August 2011; emissions on all the organic material treatments had returned to background levels (*c.*10 g N_2O-N/ha/day) by the end of November 2011 (Figure 3.9a). Net cumulative N_2O losses ranged from 0 kg N_2O/ha on the compost treatment to 1.2 kg/ha on broadcast digestate treatment. Nevertheless, the average EFs on all treatments were all less than the IPCC default value of 1% of total N applied, (Figure 3.9b). Although the EF for green/food compost was very low, and bandspreading slurry and digestate resulted in numerical reductions in the EF, none of the treatment effects were significant.

At Wensum in spring, N_2O fluxes peaked at *c.*70 g N_2O-N/ha/day in March about 1 month after the organic materials were applied in late February 2012; emissions on all the organic material treatments had returned to background levels (*c.*10 g N_2O-N/ha/day) by the end of April 2012 (Figure 3.10a). Net cumulative N_2O losses ranged from <0 kg N_2O/ha on the compost treatment to 1.8 kg/ha on the bandspread digestate treatment. Total emissions (expressed as an EF) were all less than the IPCC default value of 1% of total N applied although the variability associated with emissions from the bandspread food-based digestate and pig slurry treatments suggests that the IPCC value could be exceeded on some occasions (Figure 3.10b). Emissions from the green compost were significantly lower than from the digestate treatments and the bandspread pig slurry ($P<0.05$). There was no effect of bandspreading on the EF for digestate or pig slurry compared with surface broadcasting (Figure 3.10b).

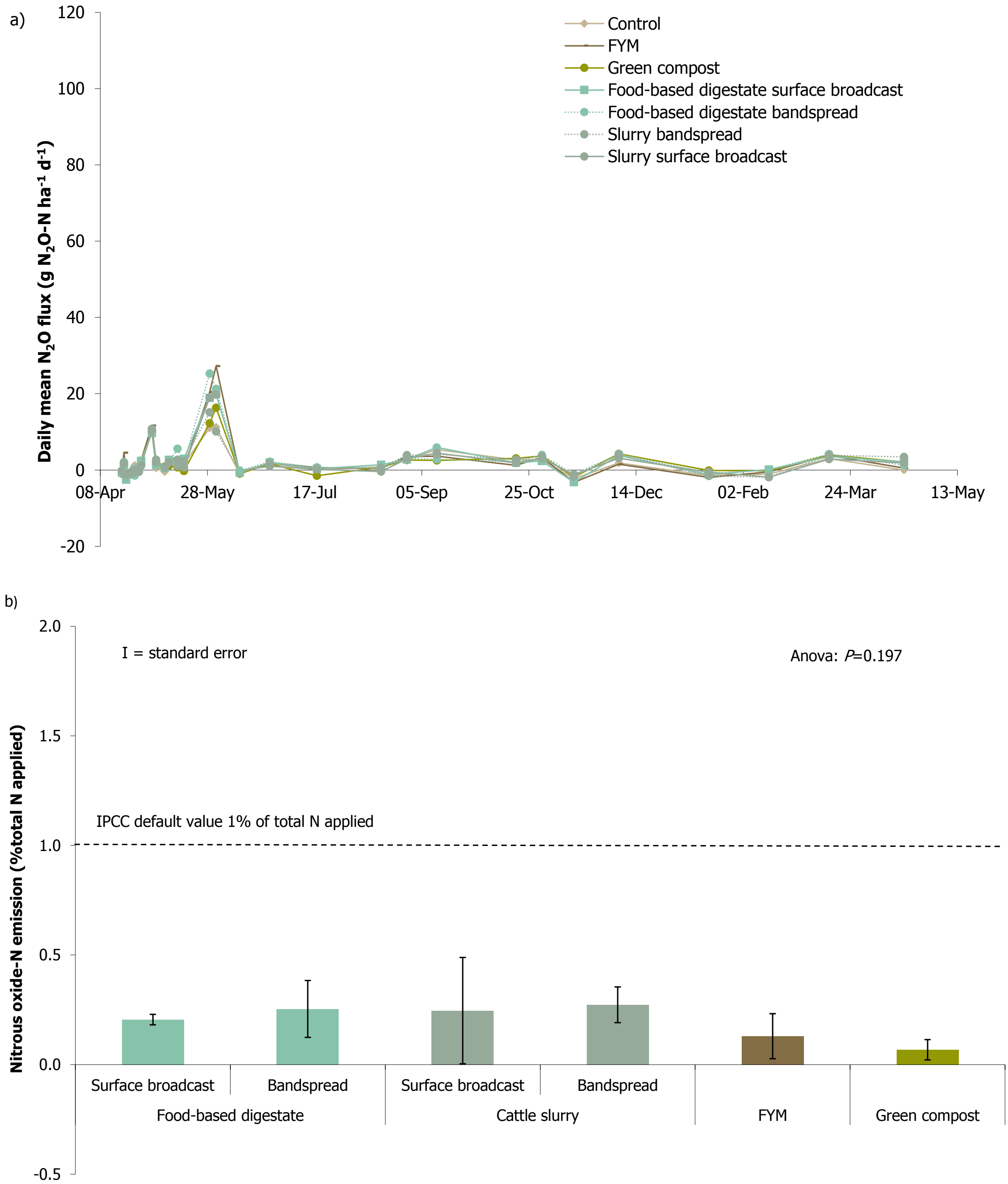

Figure 3.7 North Wyke spring: a) daily mean N_2O fluxes and b) N_2O emission factors*. No significant treatment differences .*

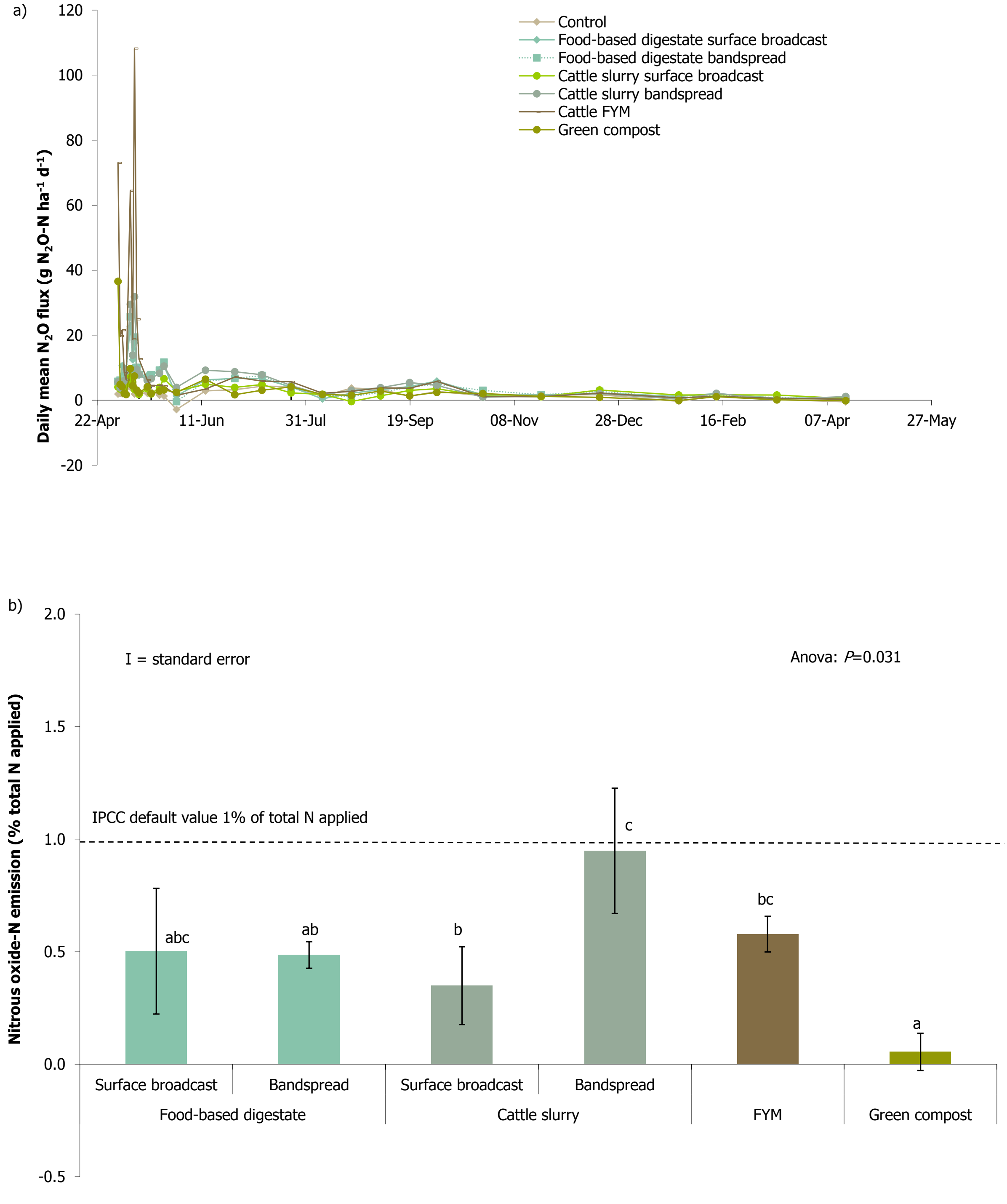

Figure 3.8. Pwllpeiran spring: a) daily mean nitrous oxide fluxes and b) emission factors. *Columns labelled with different letters are significantly (P<0.05) different from each other.*

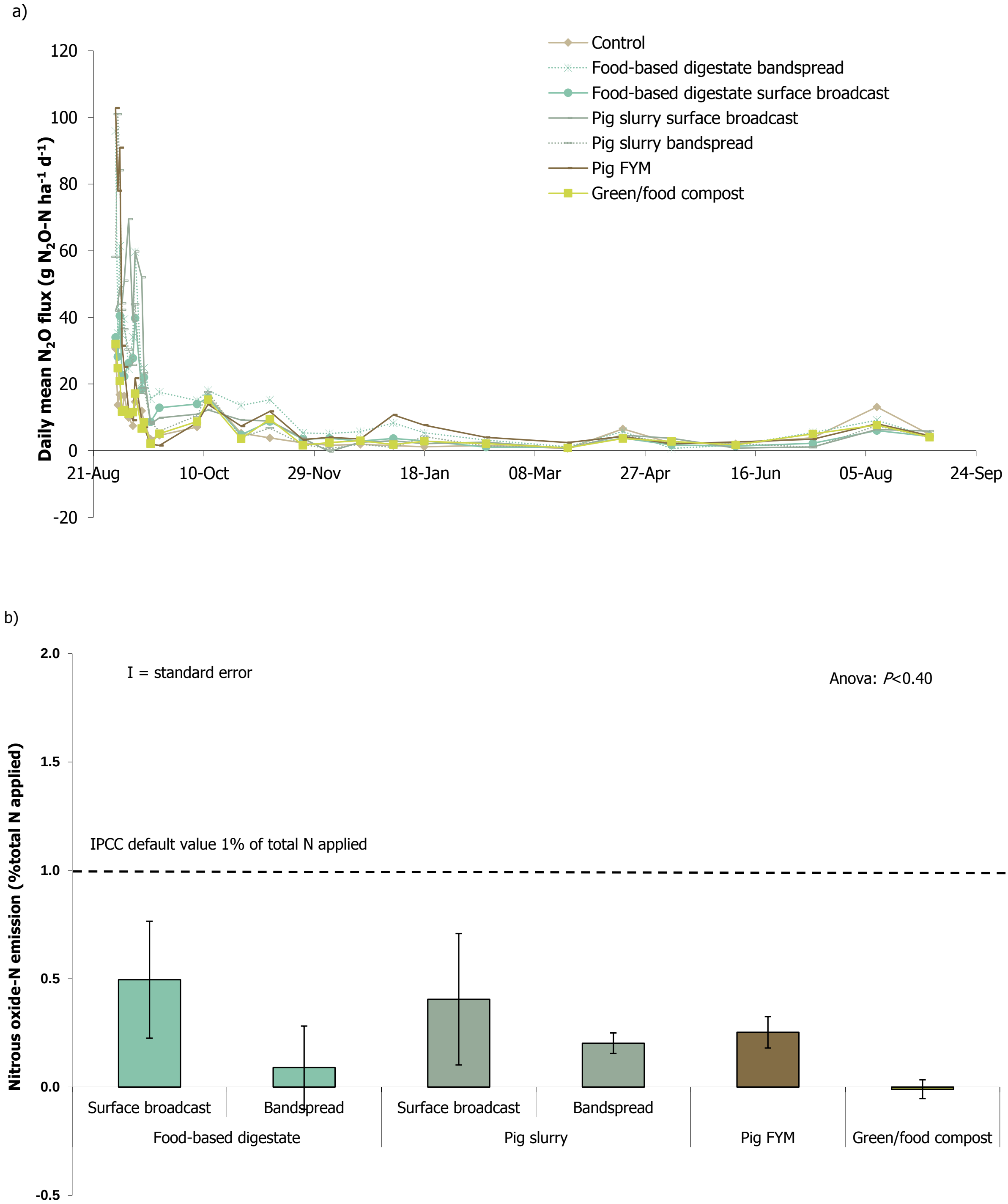

Figure 3.9 Wensum autumn: a) daily mean N_2O fluxes and b) N_2O emission factors. *No significant treatment differences.*

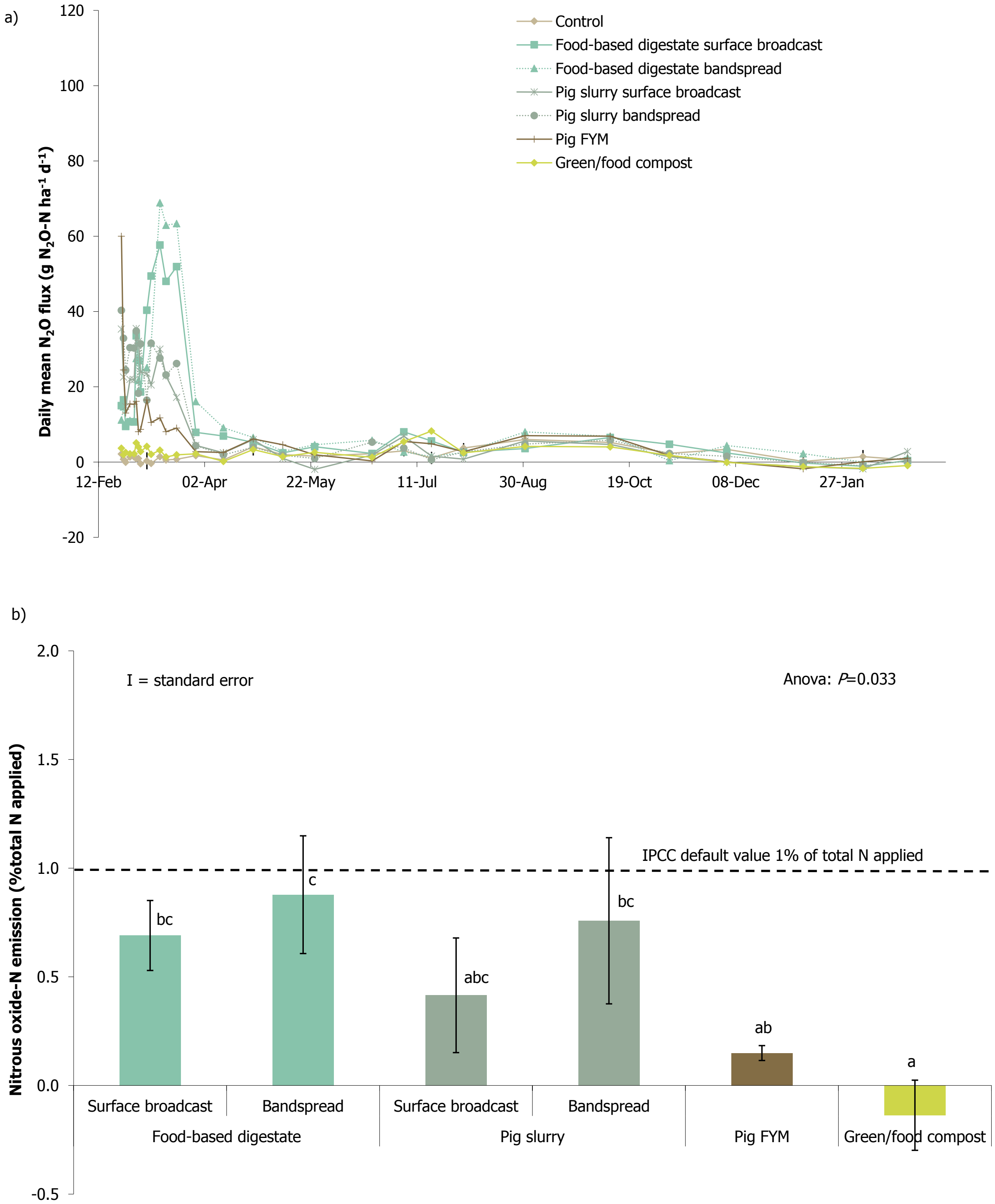

Figure 3.10 Wensum spring: a) daily mean N_2O fluxes and b) N_2O emission factors*. Columns labelled with different letters are significantly (P<0.05) different from each other.*

3.2.5 Nitrous oxide emissions - discussion

Nitrous oxide emissions from agricultural soil are predominately produced via the microbially mediated processes of nitrification and denitrification (Firestone & Davidson, 1989). The factors which control the magnitude of N_2O emission include soil mineral nitrogen (SMN) content, soil temperature and soil moisture content (Dobbie & Smith, 2001; Dobbie & Smith, 2003). The typical non-linear response of N_2O to moisture content as represented by water-filled pore space (WFPS) is shown by Davidson (1991) in Figure 3.11. This diagram indicates that there is an optimum production of N_2O, which occurs at a WFPS roughly equal to a transition point below which N_2O is predominantly emitted from the aerobic process of nitrification and above which N_2O is predominantly emitted from the anaerobic process of denitrification. Davidson (1991) suggested that this transition occurs at a WFPS of 60%; other studies, however, have shown that the position of the maximum emission can vary with soil type and conditions. Notably, UK studies have indicated that the highest N_2O emissions frequently occur as a result of the anaerobic process of denitrification i.e. at a WFPS >60% (e.g. Dobbie & Smith, 2001; Dobbie & Smith, 2003).

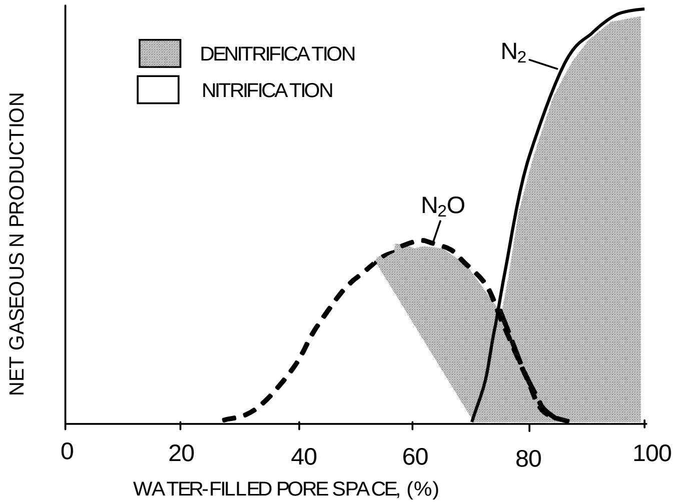

Figure 3.11 Schematic representation of the effect of water-filled pore space on emissions of N_2O and N_2, by nitrification and denitrification (Source Davidson, 1991).

At the 3 experimental sites, most N_2O emissions occurred in the few weeks following the organic materials being spread to land, and had generally returned to background levels within *c.*2 months. At North Wyke and Wensum, the highest N_2O emissions corresponded to a peak in soil ammonium-N and/or nitrate-N concentrations (see Appendix II, Figures 4, 12 and 16) suggesting that N_2O was being produced as a result of the nitrification of the ammonium-N in the applied organic materials to nitrate-N by soil micro-organisms. In this study, there was no clear relationship observed between N_2O emissions and changes in the WFPS (see Appendix II, Figures 3, 7, 11 and 15).

Nitrous oxide emissions were generally higher at Wensum (in both autumn and spring) than at North Wyke and Pwllpeiran. This may have been related to the differing weather conditions at the sites, or because the heavy clay texture of the soil at North Wyke and Pwllpeiran restricted diffusion of N_2O to the atmosphere, whereas the lighter textured soil at Wensum may have allowed increased gas diffusion resulting in greater N_2O emissions.

There was no significant effect of food-based digestate/livestock slurry application method (i.e. bandspread or broadcast) on N_2O emissions (Figure 3.12), except at Pwllpeiran where N_2O emissions were higher on the bandspread than broadcast cattle slurry treatment. This was most probably a reflection of lower ammonia emissions from the bandspread than broadcast treatment at this site (see Figure 3.2), and hence there was a larger pool of soil mineral N at risk of loss. Importantly, N_2O emission factors from all the organic material treatments were below the IPCC Tier 1 default value of 1% of total N applied, and in the case of compost was not significantly different from background values.

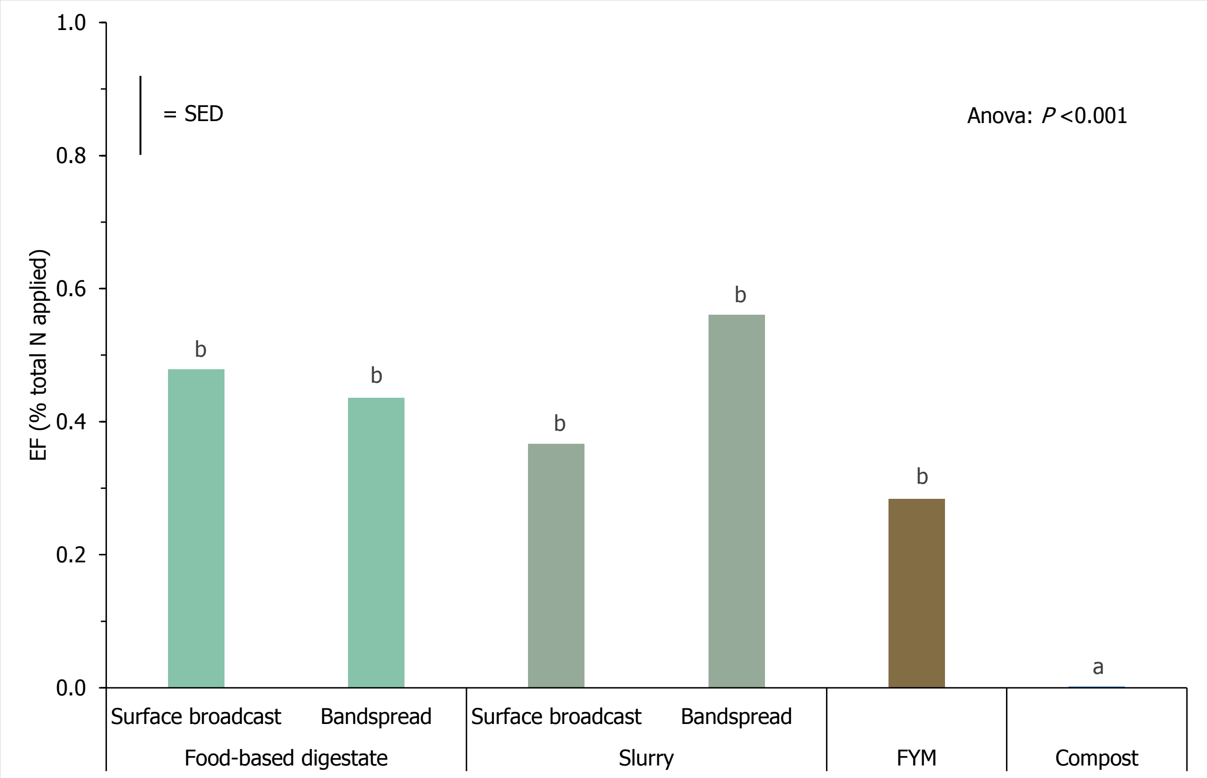

Figure 3.12 Cross site N_2O EFs. *Columns labelled with different letters are significantly (P<0.05) different from each other. SED = standard error of differences of means.*

3.2.6 Methane

Currently, the standard IPCC methodology (IPCC, 1996; IPCC, 2006) does not include a specific EF for direct methane (CH_4) emissions from soils, recognising that in most circumstances (i.e. under aerobic soil conditions) emissions are likely to be low; although, within the manure management section of the IPCC methodology it is acknowledged that there is a small emission. Indeed, well-drained aerated soils can act as a sink for CH_4 (Yamulki *et al.*, 1999).

In this study, the majority of the CH_4 emissions occurred immediately after spreading of the organic materials at all sites. For example, Figure 3.13 shows the mean daily CH_4 flux at Wensum (spring) where emissions had returned to background levels within a few days of spreading.

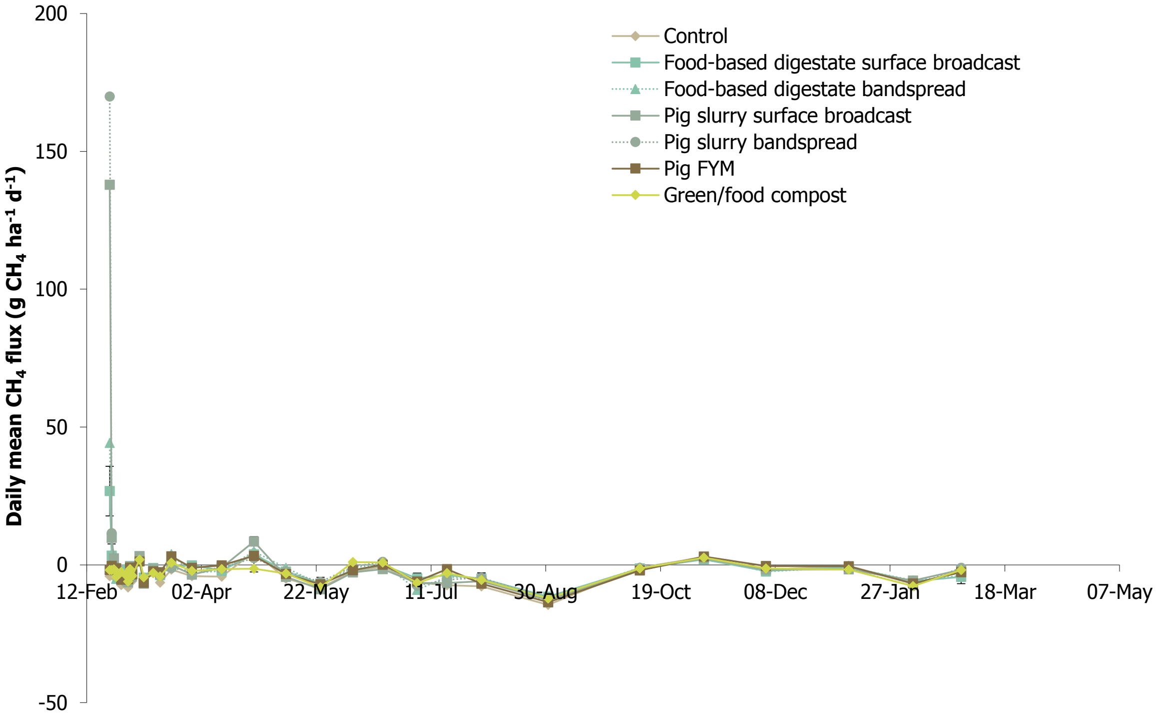

Figure 3.13 Daily mean CH_4 fluxes at Wensum (spring).

Other studies have also found that methane emissions increase following the application of organic materials to agricultural soils. Laboratory experiments carried out by Chadwick & Pain (1997) showed that CH_4 can be emitted immediately following the surface application of dairy or pig slurry to grassland, but emissions decreased to background levels after 48 hours. Such additions may lead to anaerobic soil conditions that result in CH_4 production by increasing soil moisture and through the addition of an instant supply of utilisable carbon. However, Chadwick & Pain (1997) reported that the majority of emitted CH_4 was derived from the slurry itself and not from the soil. The brevity of CH_4 emissions following the application of farm slurries to grassland was further illustrated in a field experiment, where 90% of total emissions occurred during the first 24 hours (Chadwick *et al.*, 2000). Small emissions of CH_4 were also measured following solid manure applications i.e. layer manure (*c.*45% dry matter) and beef farmyard manure (*c.*25% dry matter), with the authors suggesting that the CH_4 emissions were derived from the solid manures and not from the soil. Ball *et al.* (1994) also reported that CH_4 emissions generally only lasted for 2-3 days after the injection of liquid digested sludge or cattle slurry into grassland. Emissions from composted sewage sludge (*c.*47% dry matter) and thermally dried sludge pellets (*c.*97% dry matter) were negligible. In later years at the same site, Jones *et al.* (2005) reported that CH_4 emissions from thermally dried sludge pellets and poultry manure treatments were not different from the untreated control.

In this study, mean cumulative CH_4 emissions (on a CO_2-e basis) were calculated for *c.*21 days after spreading, by which time the emissions had returned to background levels, and were converted to a standard application rate of 250 kg/ha total N for each organic material (Table 3.5). The cumulative emissions from the solid materials (FYM and compost) were lower than from the liquids (digestate and slurry). Methane emissions from slurry were higher than from the food-based digestate, which is probably because most of the 'available' carbon in the digestates had already been lost during the anaerobic digestion process.

Indeed, as PAS110 digestates, the residual biogas (CH_4) potential is controlled and therefore the potential for CH_4 emissions following application should be low. For both the liquid organic materials, the emission from the bandspread material was consistently greater than from the broadcast applications. This may be because bandspreading a liquid organic material creates anaerobic conditions in the band which are more conducive to CH_4 production. The CH_4 emissions obtained from this study were similar to those previously calculated from measured values reported in the literature (Chadwick & Pain, 1997, Chadwick *et al.*, 2000 and Jones *et al.*, 2005), Table 3.6.

Table 3.5 Mean cumulative (*c.*21 day) CH_4 emissions (kg/ha CO_2-e) based on a 'standard' application rate of 250 kg/ha total N[1].

Organic material (application method)	Wensum autumn	Wensum spring	Pwllpeiran spring	Mean
Digestate (broadcast)	0.5	2.2	0.4	1.0
Digestate (bandspread)	1.3	2.3	2.3	2.0
Slurry (broadcast)[2]	12.3	10.0	2.0	8.1
Slurry (bandspread)[2]	20.9	11.0	4.7	12.2
FYM	0.3	0.6	-0.3	0.2
Compost	0.3	1.0	0.3	0.5
P	*<0.001*	*<0.001*	*0.034*	*0.002*

[1]Data from North Wyke not included because of problems with CH_4 analysis at this site
[2]Pig slurry at Wensum; cattle slurry at Pwllpeiran and North Wyke

Table 3.6. Mean cumulative CH_4 emissions (kg/ha CO_2-e) calculated from measured literature values (based on a 'standard' application rate of 250 kg/ha total N).

Organic material	CH_4 emission (kg/ha CO_2-e)		Number of contributing experiments[1]
	Mean	Range	
Thermally dried biosolids	0.5	-0.4 to 1.4	2
Broiler litter	1.1	-0.2 to 2.3	2
FYM	21.4	2.3 to 40.5	2
Dairy slurry	27.2	0.2 to 85.8	6
Pig slurry	10.8	0.2 to 27.3	5
Mean/Range	**15**	**-0.4 to 85.8**	-

[1]data from: Chadwick & Pain, (1997), Chadwick *et al.*, (2000) and Jones *et al.*, (2005)

3.2.7 Carbon dioxide

As organic compounds in the soil are decomposed by soil microorganisms, carbon dioxide (CO_2) is generated via respiration (enzymatic oxidation processes) (Brady, 1974). Many factors can influence the rate at which soil organic matter is broken down including temperature, soil structure (which influences how much oxygen is available in the soil), soil moisture, nutrient availability, and the quantity and nature of the organic matter present.

Currently CO_2 emissions from livestock manure (or digestate) applications are not estimated in national greenhouse gas emissions inventories because annual net CO_2 emissions are assumed to be zero – the additional CO_2 respired is removed from the atmosphere via plant photosynthesis (IPCC, 2006).

Table 3.7 Mean cumulative (12 month) CO_2 emissions (t/ha).

Organic material (application method)	Wensum autumn	Wensum spring	Pwllpeiran spring	North Wyke spring	Mean
Control	36.7	42.6^{ab}	35.2	43.4^{a}	39.5^{a}
Digestate (broadcast)	38.3	50.2^{bc}	38.6	49.7^{bcd}	44.2^{b}
Digestate (bandspread)	38.2	52.7^{c}	39.0	53.3^{d}	45.8^{b}
Slurry (broadcast)*	39.5	53.5^{c}	38.5	52.7^{d}	46.0^{b}
Slurry (bandspread)*	38.8	50.5^{bc}	40.6	47.4^{abc}	44.3^{b}
FYM	38.2	47.7^{abc}	37.4	50.9^{cd}	43.5^{b}
Compost	36.7	41.3^{a}	34.1	45.4^{ab}	39.4^{a}
P	*0.939*	*0.026*	*0.290*	*0.003*	*<0.001*

*Pig slurry at Wensum; cattle slurry at Pwllpeiran and North Wyke
Values in columns labelled with different letters are significantly different ($P<0.05$) from each other.

In this study, CO_2 emissions ranged from 0 to 500,000 g CO_2/ha/day and peaked in the summer months when temperatures were warmer (e.g. Figure 3.14). The small increases in cumulative (12 month) CO_2 emissions observed on the slurry and digestate treatments compared with the untreated control, and to a lesser extent the FYM treatment (Table 3.7), was most probably due to the additional RAN and readily decomposable carbon C supplied with these organic materials, which stimulated microbial respiration. A similar increase was not seen on the compost treatment which although adding more organic matter to the soil than the slurry and digestates, contained low amounts of total and readily available-N (see Tables 3.3 and 3.4).

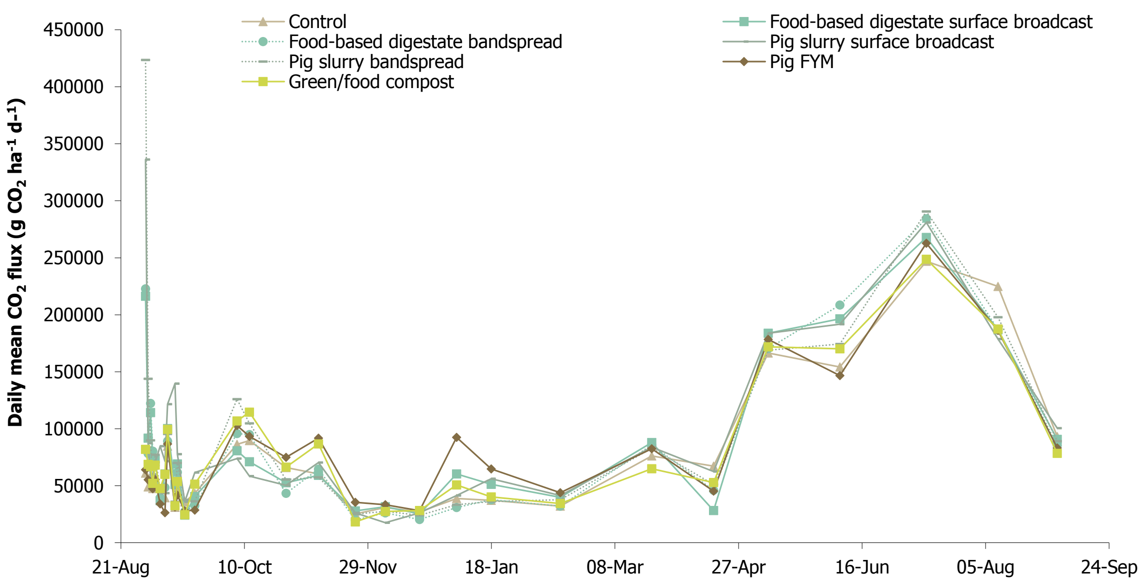

Figure 3.14 Daily mean CO_2 fluxes at Wensum (autumn 2011).

3.2.8 Leaching losses

Drainage volumes at Wensum over the winter of 2011-12 were low (92 mm) due to the lower than average over-winter rainfall of *c.*200mm compared to the 25 year average of just over 300mm.

Nitrate concentrations in the drainage water were *c.*50 mg/l on all treatments at the start of drainage in November/December 2011; concentrations peaked in January/February 2012 and were highest (*c.*130 mg/l) on the surface broadcast food-based digestate treatment. Cumulative nitrate leaching losses following the food-based digestate and pig slurry treatments were greater ($P<0.05$) than from the pig FYM and compost treatments, with no significant differences between bandspread and broadcast food-based digestate treatments (Figure 3.15). Ammonium-N concentrations in the drainage waters were very low on all treatments (<0.05 mg/l) and cumulative leaching losses were <0.02 kg/ha (i.e. <0.01% of the total N applied).

Phosphorus (P) concentrations in the drainage waters peaked in late November/early December 2011 but did not exceed 0.3 mg/l on any treatment and had returned to background levels (*c.*0.05 mg/l) by the start of January 2012. Cumulative P leaching losses were low (<0.05 kg/ha) from all the treatments with no significant differences between the organic material treatments and the untreated control (Figure 3.16). *E.coli* were not detected in any of the drainage waters sampled even where organic materials had been applied.

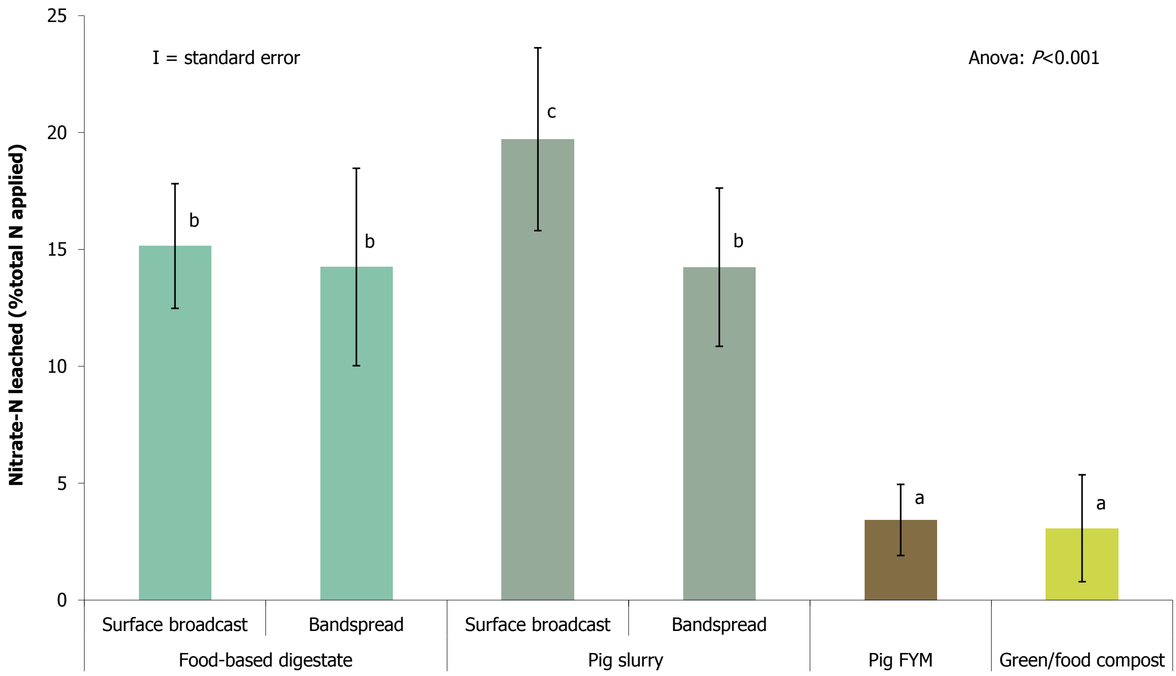

Figure 3.15. Leaching losses (% of total N applied) following the autumn 2011 organic material applications. *Columns labelled with different letters are significantly (P<0.05) different from each other.*

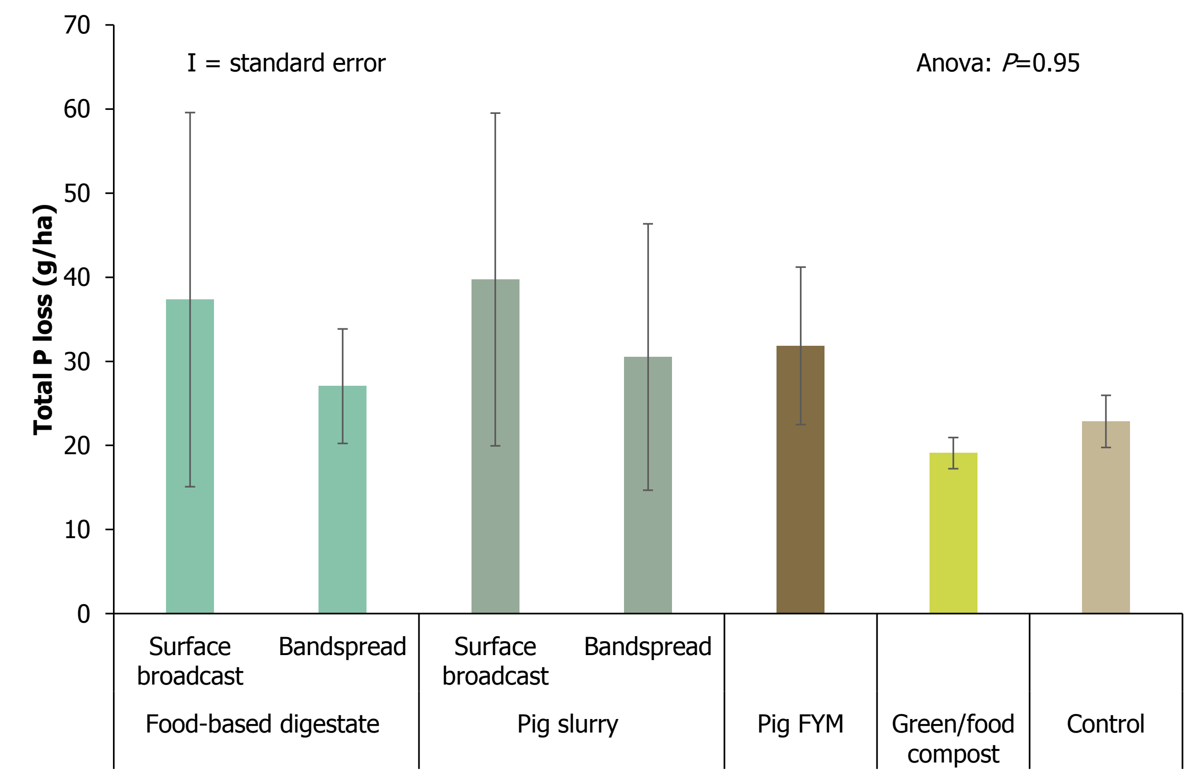

Figure 3.16. Phosphorus leaching losses (g/ha) following the autumn (31 August) 2011 organic material applications at Wensum.

3.2.9 Crop N offtakes

The effects of the different treatments on crop yields and N offtake were discussed in Section 2, the detailed data is shown in Appendix I.

3.2.10 N balances

Nitrogen losses via ammonia volatilisation, N_2O (and di-nitrogen – N_2) emissions and nitrate leaching were combined with the crop N offtake data to construct N balances for each organic material application strategy at Wensum and Pwllpeiran (Figures 3.17 – 3.18). A complete N balance could not be constructed for North Wyke because neither grass yields nor N offtakes responded to N applied as inorganic fertiliser or in the organic materials (see Work Package 2.1). *Note that N_2 emissions were estimated from N_2O losses using the methodology developed for the MANNER-NPK software tool and detailed in Nicholson et al. (2013).*

At Wensum in autumn 2011, 55-75% of the total N applied in food-based digestate and pig slurry was lost as ammonia, N_2O/N_2 to the atmosphere and via nitrate leaching to groundwater (Figure 3.17). In spring 2012, losses to the environment were smaller at 20-30% of the total N applied. Environmental emissions from pig FYM and compost were much smaller at 10-15% of N applied in autumn and <5% in spring. Crop N uptake from the food-based digestate and slurry was higher in spring than in autumn, although only *c.*40-50% of the total N applied was accounted for in the N balance, compared with *c.*75-90% from the autumn applications. At Pwllpeiran, the N measured in the grass crop and as gaseous N emissions ranged from <5% of total N applied (compost) to 80-90% of total N applied (food-based digestate), Figure 3.18.

The N that was not measured in crop offtakes or environmental emissions is most likely to have been retained in the soil in an organic N form; particularly as most of this 'unaccounted

N' was associated with the solid organic material treatments, where a large proportion of the total N applied was in organic forms. This N would not be immediately available for crop uptake, but could help to build soil total N stocks in the longer term for future mineralisation to plant available forms, thereby contributing to crop N requirements and reduced mineral N fertiliser costs.

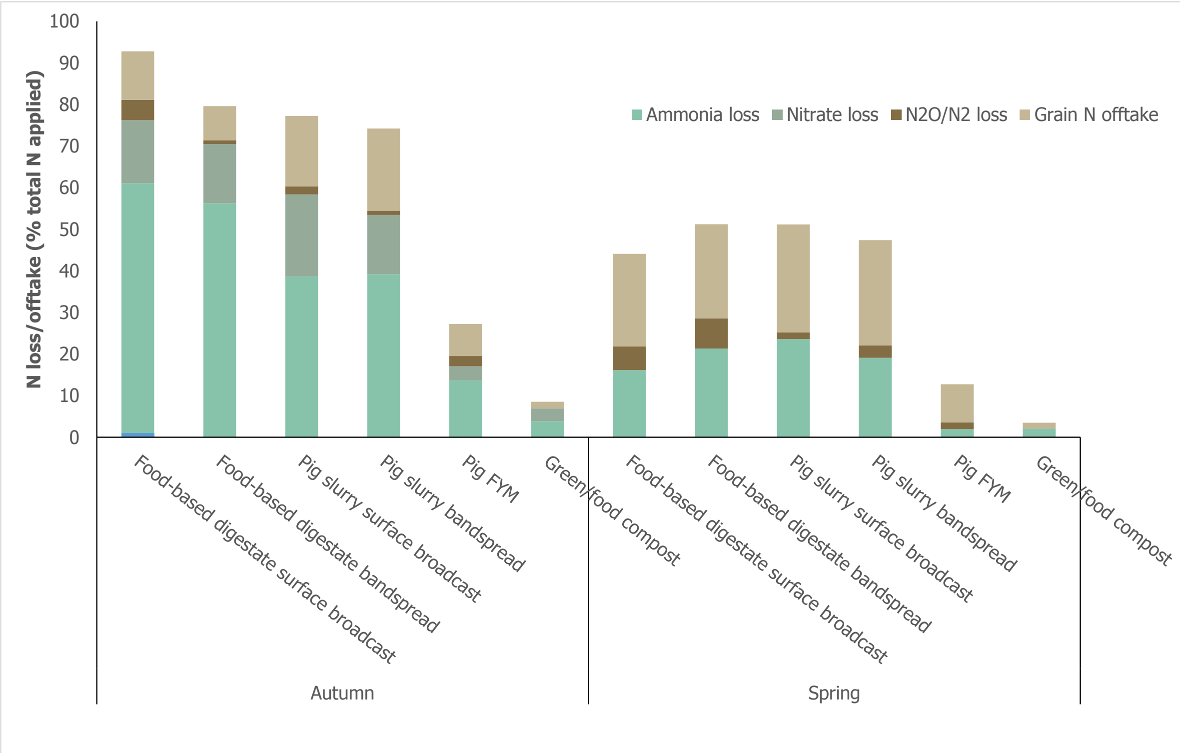

Figure 3.17. N balance for Wensum autumn 2011 and spring 2012.

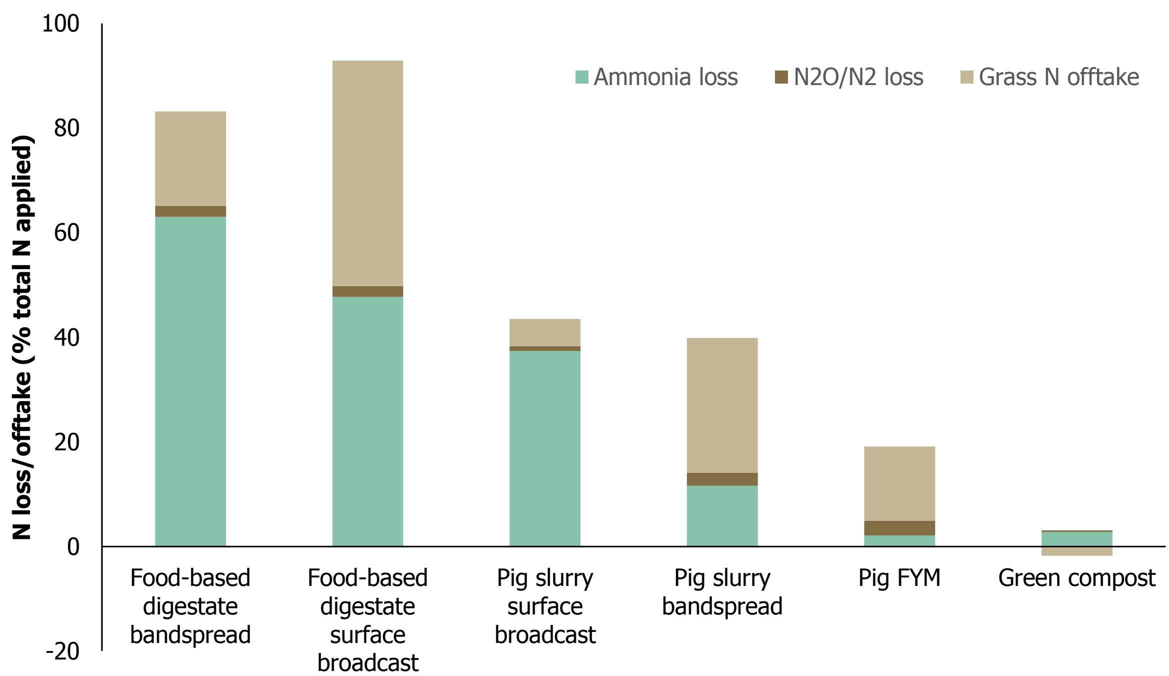

Figure 3.18. N balance for Pwllpeiran spring 2012.

3.3 WP2.2 Conclusions

Digestate. The results of this study have shown that ammonia emissions following land spreading of food-based digestates were high at both the arable and grassland sites (30-50% of total N applied). This was due to the relatively high pH of the food-based digestates (mean 8.5) and the soil conditions at the time of spreading which affected the rate at which the materials infiltrated into the soil matrix. Precision application (i.e. bandspreading) can reduce ammonia emissions, but the effectiveness of these techniques is dependent on the prevailing soil conditions or length of grass. The importance of grass length as a factor affecting ammonia emissions is not clear; previous UK/Danish research has shown that the abatement efficiency of bandspread slurry applications increased with grass crop height and was typically 60% (Thorman *et al*, 2008). In contrast, more recent Irish data (Lalor *et al.*, 2012) has not supported a relationship between ammonia emission reductions from bandspread applications and grass crop height.

Because the majority of the ammonia losses occurred within 6 hours of spreading, it is important that farmers are encouraged to rapidly incorporate digestates into the soil as a method for conserving N so it can be utilised by the crop. In contrast, N_2O losses from all the digestates were low, with measured emission factors (EFs) all less than the 1% IPCC default value (mean 0.45 ± 0.15%). Nitrate leaching losses were shown to be much higher from autumn food-based digestate applications than from spring applications, strongly suggesting that farmers should be advised to apply these materials in the spring where practically possible. Losses of soluble phosphorus were equal to those of the untreated control, as were the methane and CO_2 emissions, and no viable *E.coli* were detected in drainage waters.

Compost. Emissions (ammonia, N_2O, methane, CO_2, nitrate and soluble P*)* from green compost were all low and no viable *E.coli* were detected in drainage waters, indicating that in these terms compost can be considered as an 'environmentally benign' material, which can be used to build up soil long-term (organic) N reserves.

The information produced from this study can be used to develop best practice guidelines for digestate and compost use that seek to maximise crop nutrient utilisation and to minimise emissions to air (as ammonia, nitrous oxide and methane) and water (as nitrate, phosphorus and microbial pathogens).

4. WP2.3 Application techniques

4.1 Introduction

Minimising ammonia (NH_3) emissions following the land application of digestate is important to maximise crop available N supply and reduce the environmental impact of recycling digestate to agricultural land.

This work package evaluated the effect of shallow injected digestate applications to grassland on crop available N supply and ammonia emissions, compared with conventional surface broadcast and bandspread (trailing shoe) applications.

4.2 Methodology

4.2.1 Experimental site

The three application technique sites (Aberaeron, Beith and Newark) were established on a range of soil types and agroclimatic areas in autumn 2010 (see Figure 2.2 and Table 2.1 in Section 2). The soil at each sites was characterised as described in Section 2. Topsoil bulk density and available water capacity was also measured using standard methods (Anon, 1982).

4.2.2 Treatments and design

At each site, there were 3 replicates of the following treatments, arranged in a randomised block design, viz:

1 Untreated control
2 Surface broadcast food-based digestate
3 Bandspread (trailing shoe) food-based digestate
4 Shallow injected food-based digestate
5 Surface broadcast cattle slurry
6 Bandspread (trailing shoe) cattle slurry
7 Shallow injected cattle slurry
8 Manufactured fertiliser at 30 kg N/ha
9 Manufactured fertiliser at 60 kg N/ha
10 Manufactured fertiliser at 90 kg N/ha
11 Manufactured fertiliser at 120 kg N/ha
12 Manufactured fertiliser at 150 kg N/ha

The liquid organic material applications were made using the ADAS purpose-designed small plot applicator (as per Section 3) to broadcast, bandspread and shallow inject liquid organic materials accurately and evenly over the width and length of the plots. Target application rates were in the range 100-150 kg/ha total N (e.g. 30 m3/ha) (depending on the N content of the liquid organic materials) and complied with the requirements of the Nitrate Vulnerable Zones Action Programme i.e. the organic manure N field limit of 250 kg/ha total N (SI, 2008; SSI, 2008; WSI, 2008).

4.2.3 Organic material analysis

At each site and application timing, a representative sample of each organic material type from each block was taken at spreading (*c.*2 litres per block for each liquid organic material and *c.*2 kg per block for each solid organic material) and analysed for dry matter, pH, total N, ammonium-N and nitrate-N using standard methodologies (MAFF, 1984).

4.2.4 Crop management

The grass was grown according to best farm practice using crop protection products applied as needed and according to good agricultural practice to control weeds, pests and diseases. All treatments had manufactured fertilisers (P_2O_5, K_2O & SO_3) applied based on the requirements of the untreated control (Defra, 2010b) to ensure that only N limited grass growth. All recommendations were checked by a FACTS qualified adviser.

4.2.5 Ammonia emissions

The wind tunnel methodology described in Section 3 was used to measure ammonia emissions for seven days after organic material applications.

4.2.6 Harvest

Grass yields were measured at first cut using a mechanical grass harvester. Samples of cut grass were analysed for N, P, K, Mg, S and dry matter content.

4.3 Results

4.3.1 Ammonia emissions

Site 1. Aberaeron

Ammonia emissions following the autumn 2013 organic material applications at Aberaeron ranged from 16% (cattle slurry shallow injected) to 41% (food-based digestate surface broadcast) of total N applied, although there were no statistically significant differences between the treatments (*P*=0.05), Figure 4.1.

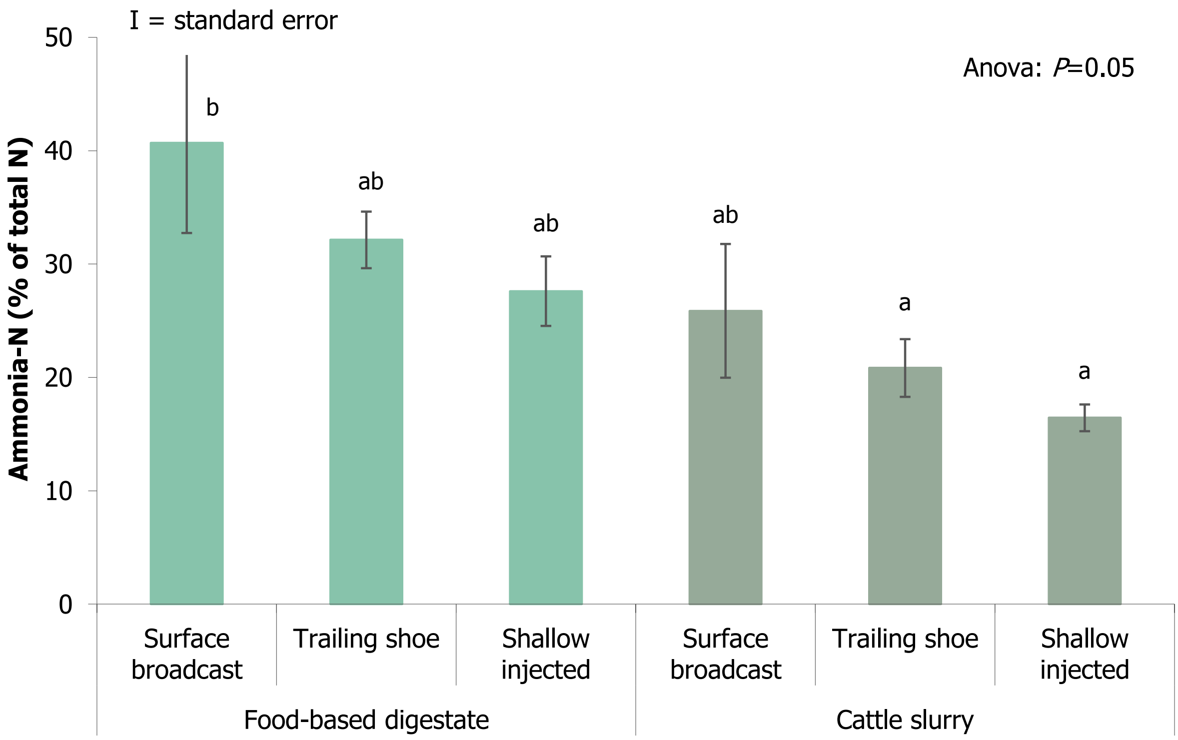

Figure 4.1. Aberaeron autumn 2013 ammonia emissions.

Although not confirmed statistically, there was a tendency for the trailing shoe and shallow injection methods to reduce ammonia emissions compared with surface broadcasting. Emissions from the food-based digestate treatments were numerically higher than those from the cattle slurry treatments, reflecting the greater ammonium content of digestate (3.7 kg/m^3) compared with cattle slurry (1.4 kg/m^3) and its higher pH (pH 8.4 for food-based digestate and pH 8.0 for cattle slurry); pH levels greater than 8 are likely to enhance ammonia emissions from applications of organic materials. The dry matter contents of the food-based digestate and cattle slurry were similar and hence were not likely to have influenced ammonia emissions.

Ammonia emissions following the spring 2014 organic material applications at Aberaeron were lower than in the autumn and ranged from 8% (food-based digestate trailing shore) to 24% (cattle slurry surface broadcast) of total N applied, with significant differences between treatments (*P*<0.001), Figure 4.2.

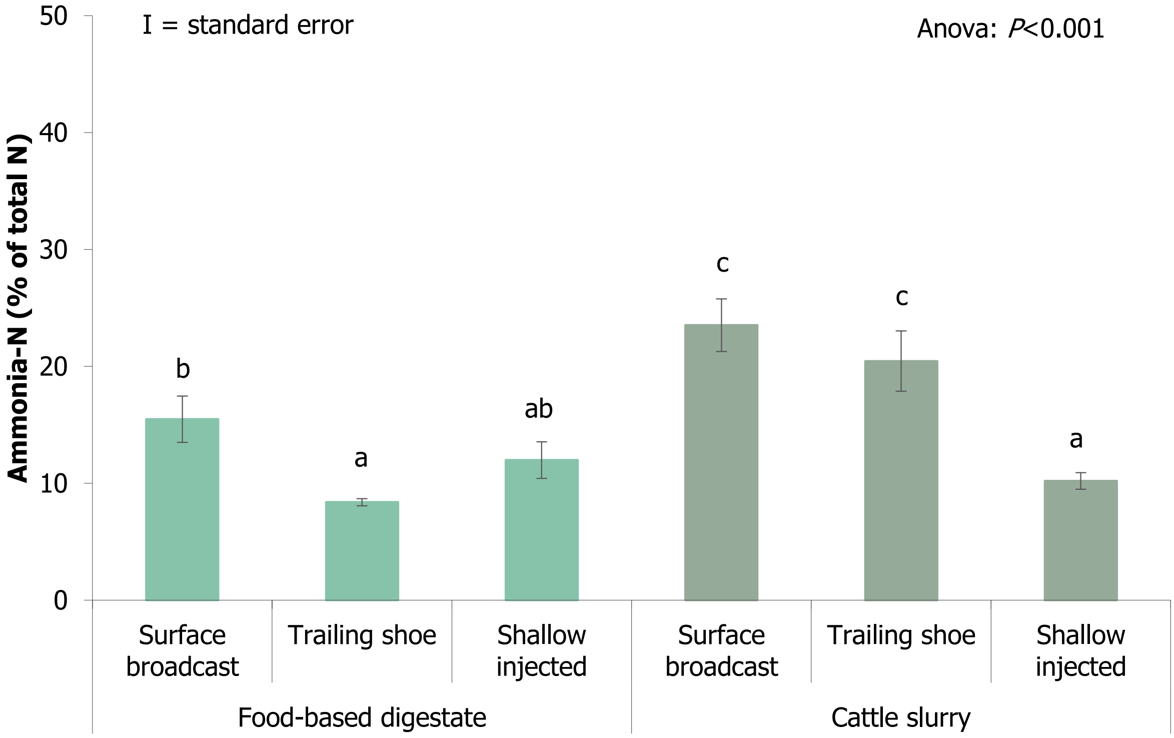

Figure 4.2. Aberaeron spring 2014 ammonia emissions. *Columns labelled with different letters are significantly (P<0.05) different from each other*.

The lower ammonia emissions from the food-based digestate treatments compared with the cattle slurry treatments was most probably due to the lower dry matter content of the food-based digestate (2.1% compared with 4.8% for the cattle slurry) which allowed more rapid infiltration into the soil, reducing the potential for ammonia loss.

Site 4. Beith

Ammonia emissions following the autumn 2013 organic material applications at Beith ranged from 6% (cattle slurry shallow injected) to 29% (food-based digestate surface broadcast) of total N applied with significant difference between treatments (*P*=0.002), Figure 4.3.

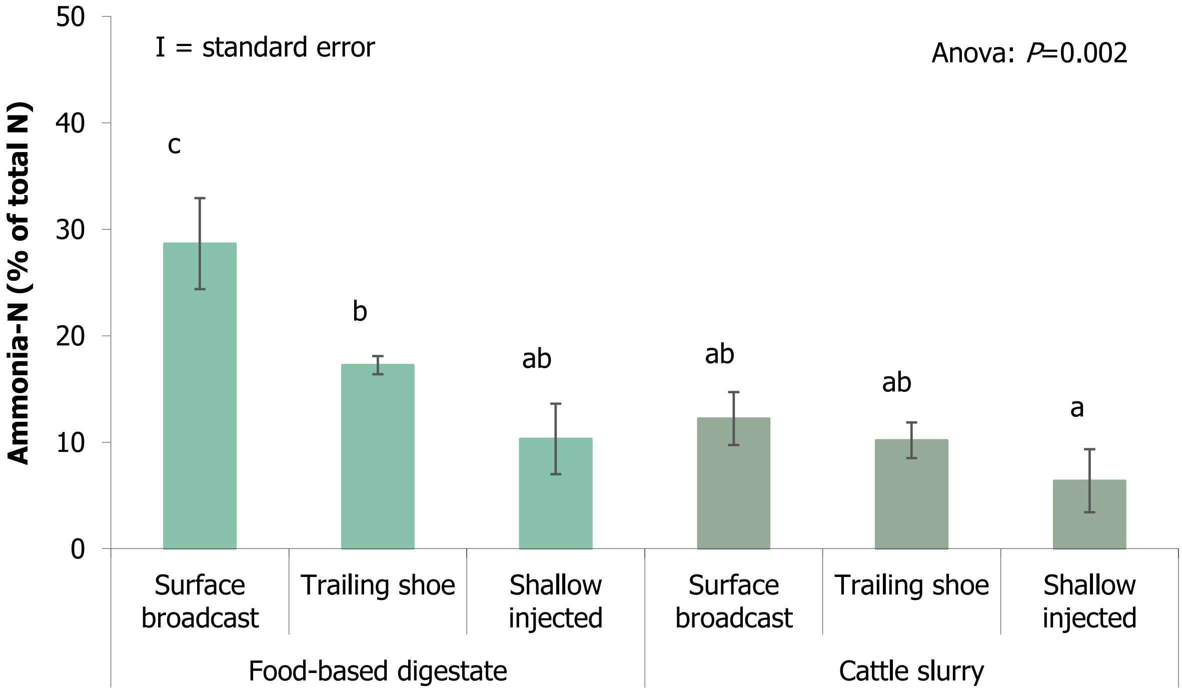

Figure 4.3. Beith autumn 2013 ammonia emissions. *Columns labelled with different letters are significantly (P<0.05) different from each other*.

For the food-based digestate, both the trailing shore and shallow injection methods reduced ammonia emissions compared with surface broadcasting, although this was not the case for the cattle slurry. The higher ammonia emissions from the surface broadcast food-based digestate compared with the surface broadcast cattle slurry was most probably due to the higher ammonium and pH (2.5 kg/m^3 and pH 8.5) of the food-based digestate compared with cattle slurry (1.3 kg/m^3 and pH 7.8).

Ammonia emissions following the spring 2014 organic material applications at Beith ranged from 5% (cattle slurry shallow injected) to 23% (food-based digestate surface broadcast) of total N applied, with significant difference between treatments ($P<0.001$), Figure 4.4.

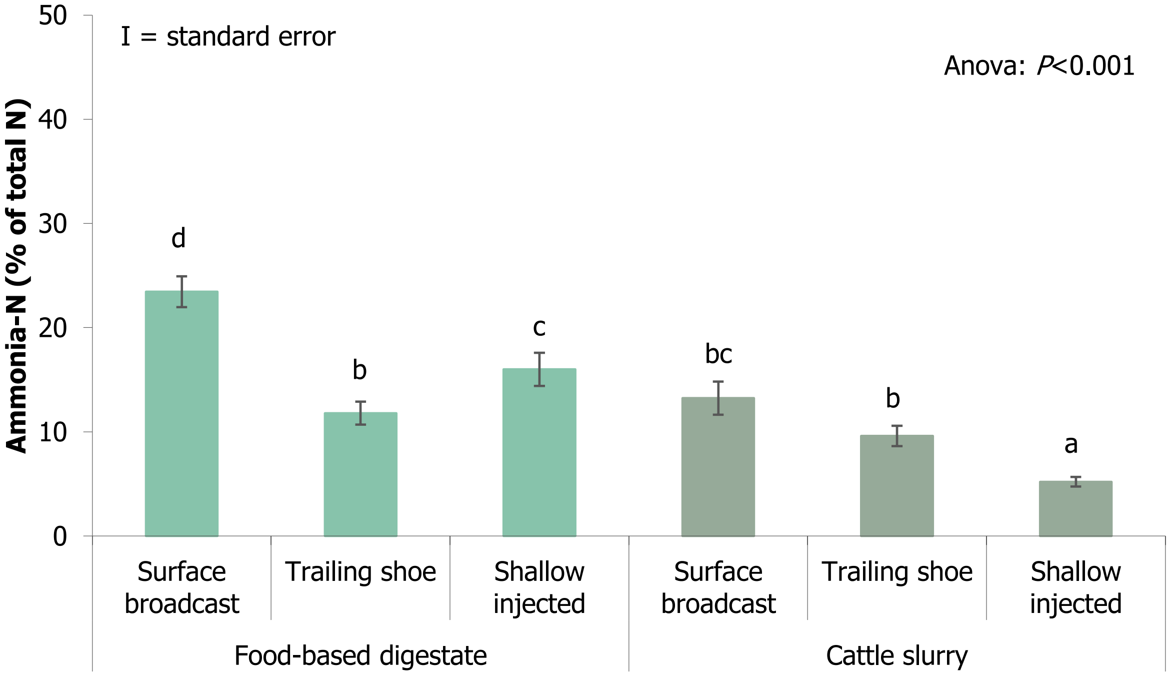

Figure 4.4. Beith spring 2014 ammonia emissions. *Columns labelled with different letters are significantly (P<0.05) different from each other.*

Both the trailing shoe and shallow injection application methods significantly ($P<0.05$) reduced ammonia emissions from the food-based digestate compared with surface broadcasting, whilst only shallow injection reduced ammonia emissions from cattle slurry. For food-based digestate, the trailing shoe application method outperformed the shallow injection treatment. This is most probably a result of a slight smearing of the injection slot, due to the soil being damp at the time of application, which reduced infiltration of the food-based digestate. Nevertheless, ammonia emissions from the shallow injection treatment were lower than from the surface broadcast treatment despite the reduced infiltration into the soil.

Site 11. Newark

Ammonia emissions following the autumn 2013 organic material applications at Newark ranged from 8% (cattle slurry shallow injected) to 39% (food-based digestate surface broadcast) of total N applied, with significant difference between treatments ($P<0.001$), Figure 4.5.

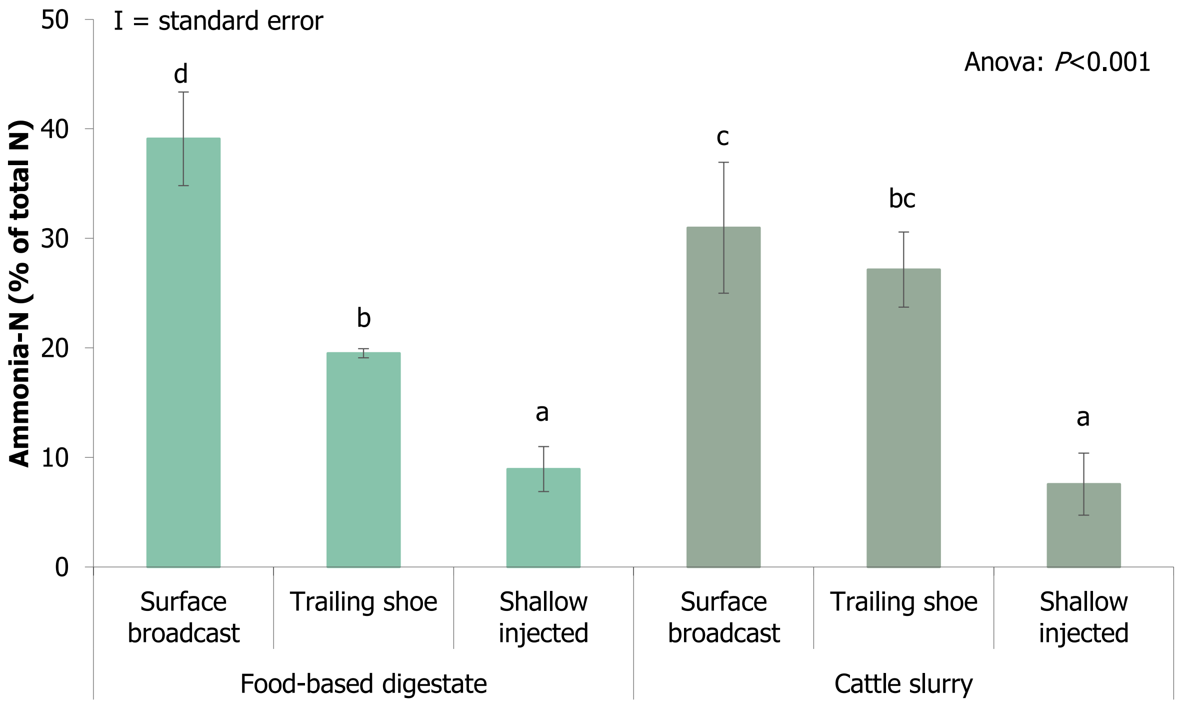

Figure 4.5. Newark autumn 2013 ammonia emissions. *Columns labelled with different letters are significantly (P<0.05) different from each other*.

Both the trailing shoe and shallow injection application methods significantly (*P*<0.05) reduced ammonia emissions from the food-based digestate compared with surface broadcasting, whilst only shallow injection reduced ammonia emissions from cattle slurry. Ammonia emissions from the surface broadcast food-based digestate were higher than from the surface broadcast cattle slurry applications probably because of the higher ammonium content of the digestate (5.3. kg/m^3 compared with 2.6 kg/m^3 for the cattle slurry).

Ammonia emissions following the spring 2014 organic material applications at Newark ranged from 11% (food-based digestate shallow injected) to 41% (food-based digestate surface broadcast) of total N applied, with significant difference between treatments (*P*<0.001), Figure 4.6.

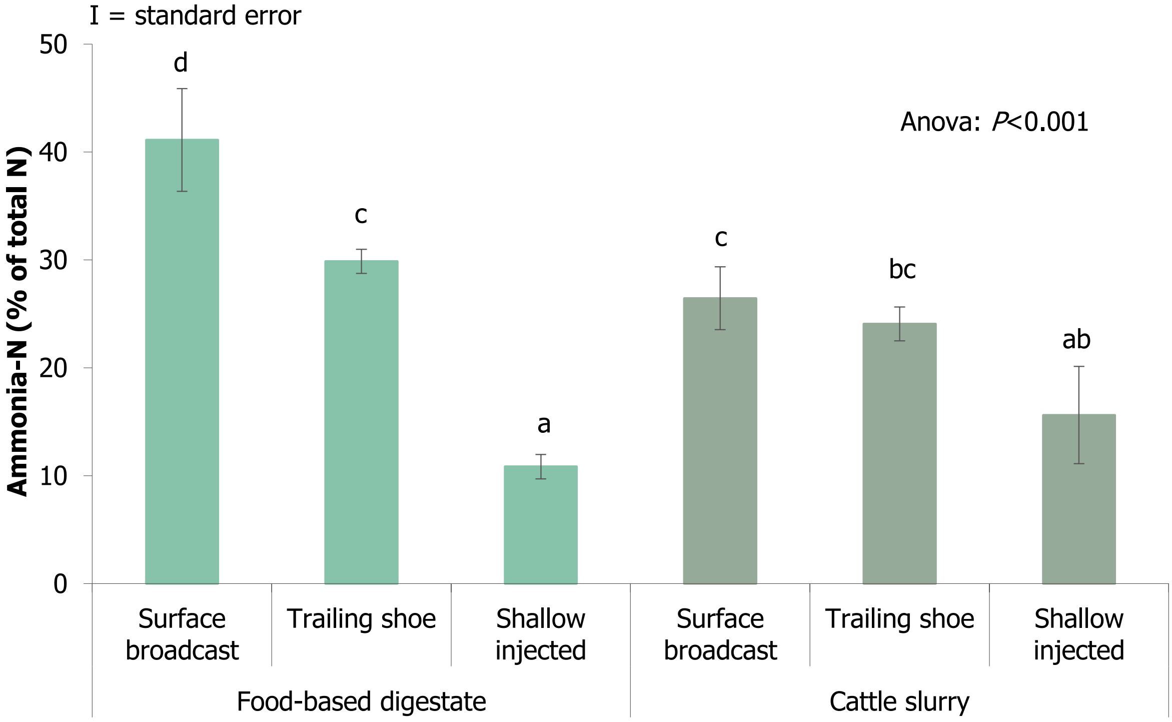

Figure 4.6. Newark spring 2014 ammonia emissions. *Columns labelled with different letters are significantly (P<0.05) different from each other.*

Both the trailing shoe and shallow injection application methods significantly ($P<0.05$) reduced ammonia emissions from the food-based digestate compared with surface broadcasting, whilst only shallow injection reduced ammonia emissions from cattle slurry. Ammonia emissions were higher from the surface broadcast food-based digestate compared with the surface broadcast cattle slurry, reflecting the elevated ammonium content of the food-based digestate (4.4 kg/m^3) compared with the cattle slurry (2.3 kg/m^3).

Cross-site analysis

Cross-site analysis of data from the three sites (Figure 4.7) confirmed the findings from the individual sites, namely:

- Both the trailing shoe and shallow injection application methods significantly ($P<0.05$) reduced ammonia emissions from the food-based digestate by 40-50% compared with surface broadcasting, although there was no significant difference between the effectiveness of the trailing shoe and shallow injection techniques.
- Only shallow injection reduced ($P<0.05$) ammonia emissions from cattle slurry compared with surface broadcasting; a reduction of *c.*50% was achieved.
- Ammonia emissions were around 40% higher ($P<0.05$) from the surface broadcast food-based digestate compared with the surface broadcast cattle slurry, reflecting the elevated ammonium-N content and higher pH of the food-based digestate compared with the cattle slurry.

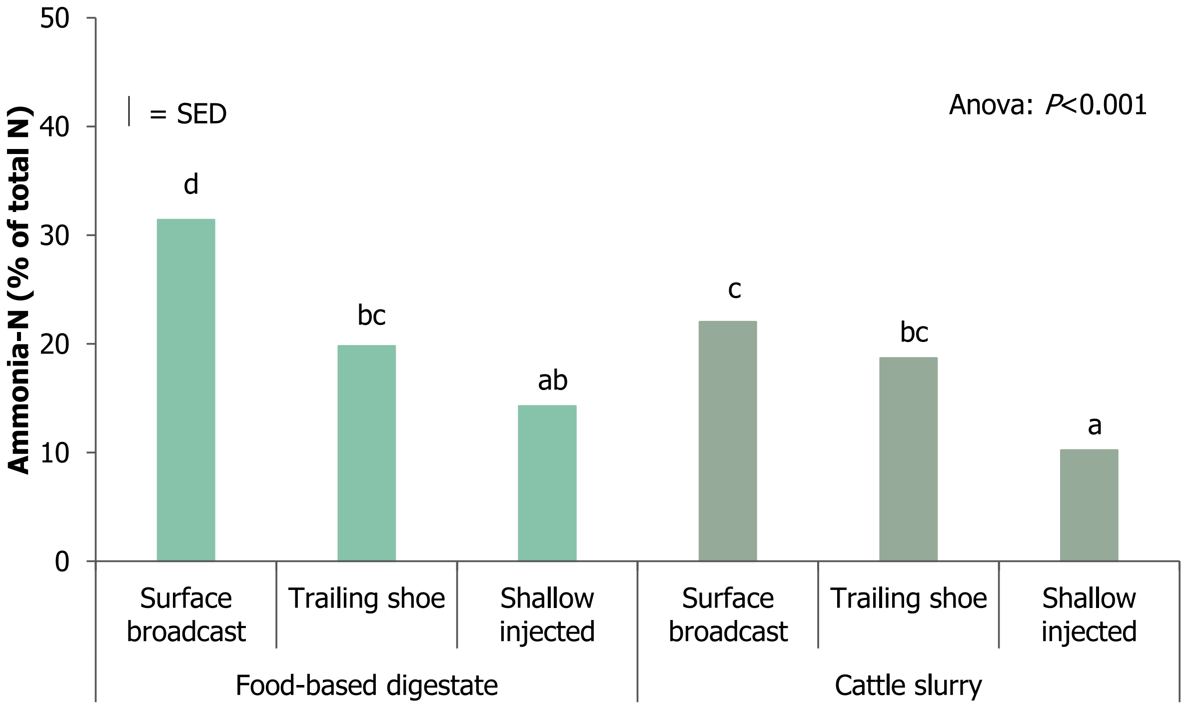

Figure 4.7 Cross-site ammonia emissions. *Columns labelled with different letters are significantly (P<0.05) different from each other. SED = standard error of differences of means*

4.3.2 Crop N offtakes

The effects of the different treatments on crop yields and N offtake were discussed in Section 2, the detailed data is given in Appendix I.

4.4 Discussion

The assessments of the effectiveness of precision application techniques in reducing ammonia emissions compared with broadcast applications in this study are comparable with other field-based experimental studies. The Defra-funded 'SLURRY-*NR*' project (Defra, 2007) investigated the effectiveness of application technique (as well as application rate) on ammonia emissions (in addition to nitrous oxide emission, nitrate leaching losses and crop N uptake) from livestock slurries applied to arable and grassland. Shallow injection applications to grassland were found to reduce ammonia emissions by *c.*50% compared with surface broadcast, and trailing shoe applications to grassland reduced ammonia emissions by *c.*30%. Similar ammonia reduction figures have been reported in numerous other studies using livestock slurries (Smith *et al.*, 2000; Huijsmans *et al.*, 2001; Misselbrook *et al.*, 2002; UNECE, 2007; Thorman *et al.*, 2008, Lalor *et al.*, 2012).

Although data from this study and the published literature have demonstrated the effectiveness of shallow injection to grassland soils, the greater susceptibility of shallow injection to the prevailing soil conditions was also highlighted. Specifically, in this project problems were experienced where soils were wet, leading to smearing of the injection slot which reduced infiltration of the digestate and slurry into the soil. Other problems that have been reported with shallow injection include high stone content which prevents discs cutting the injection slot and can damage equipment, and uneven ground which can also prevent the discs cutting the injection slot). Other studies have also found that when injection works and soil conditions are appropriate then the technique is effective, but when they are not, ammonia emissions are not reduced compared with broadcast applications and can even be elevated (Smith *et al.*, 2000; Misselbrook *et al.*, 2002; Defra, 2007). However, due to the widths of the commercial spreading equipment, (typically between 4 and 8m), shallow injection is not ideally suited to arable land. This is because tramlines would need to be split potentially damaging the growing crop (except for applications before autumn drilling e.g. ahead of oilseed rape). As such, it is highly unlikely that shallow injection application techniques will ever be widely utilised on arable land.

The data gathered from this study have also demonstrated the effectiveness of trailing shoe techniques for reducing ammonia emissions from food-based digestate applications to grassland. Although reductions in emissions may not be as great as with injection, this method is less affected by soil conditions, which together with lighter equipment, enables greater opportunity for spreading in wet springs. For grasslands, the trailing shoe can also lead to greater reductions in ammonia emissions compared to bandspreading, particularly when the sward is long, as the shoe parts the grass canopy to place the digestate/slurry on the soil surface, compared to a bandspreader which places it on top of the grass (Misselbrook *et al.,* 2002).

In addition to reducing ammonia emissions, the use of all precision application techniques brings a number of other important benefits compared with surface broadcasting, including reduced odour nuisance and crop contamination, a greater number of spreading days (as the grass needs to be clean before livestock can graze/grass can be cut; in addition to the statutory no graze/harvest intervals if applicable), increased N efficiency (as a result of reduced ammonia emissions and the ability to apply the digestate to growing crops in spring to reduce nitrate leaching losses). The precision techniques also ensure even application of digestate which is particularly important considering the high readily available N content (typically 80% of total N).

4.5 Conclusions

Both precision application methods reduced ammonia emissions from food-based digestate by 40-50% in comparison with the surface broadcast treatments. In this study there was no difference between the effectiveness of the trailing shoe and shallow injection techniques when used with food-based digestate, however shallow injection was more effective than trailing shoe for cattle slurry applications, reducing ammonia emissions by *c.*50% compared with surface broadcasting.

The use of shallow injection when applying liquid organic materials (i.e. food-based digestate) to grassland is an important method for reducing ammonia emissions. However, it is more sensitive to soil conditions (e.g. wetness and stone content) than other application methods, which may be a barrier against its more widespread adoption.

5. Overall conclusions and recommendations

5.1 Digestate

The mean nitrogen (N) use efficiency (NUE) of spring bandspread food-based digestate measured in replicated field experiments was 54 ± 7% of total N applied. This was reduced to 13 ± 4% of total N applied when food-based digestate was bandspread in the autumn, highlighting the effect of N losses via overwinter nitrate leaching. Manure-based digestate applied in spring had a mean NUE of 52 ± 8% which decreased to 15 ± 6% of total N applied for autumn applications. For both materials, there was considerable variation between the NUE results obtained from the individual experimental sites; however, this was not surprising given the complexity and interactions of the processes involved and is also the case for other organic material applications (e.g. livestock slurries).

MANNER-*NPK* estimates of NUE compared well with the field measurements, indicating that MANNER-*NPK* is a useful tool for farmers and advisors who want to account for the nitrogen content of food-based and manure-based digestates when developing fertiliser strategies. However, there is scope for the MANNER-*NPK* estimates to be further improved by incorporating information on environmental N losses from digestates into the MANNER-*NPK* calculation algorithms. Importantly, data on digestate composition and NUE obtained in this study could be included in the forthcoming revisions to the Fertiliser Manual (RB209) to ensure that advice for farmers and advisors on digestate utilisation is up to date and robust.

There were sizable ammonia emissions from the food-based digestates (*c.*40% of total N applied) compared to livestock slurry (*c.*30% of total N applied); this is partly due to the greater ammonium content of the food-based digestate and partly to its elevated pH (mean 8.3). Ammonia emissions were reduced on grassland where the food-based digestate was applied via trailing hose (39 ± 6% reduction) and particularly when it was applied via shallow injection (50 ± 12% reduction). However, good soil conditions are required for shallow injection to operate to its full potential (i.e. soils should not be too wet or stoney). On arable land bandspread applications did not reduce ammonia emissions compared to broadcast applications. Because of the potentially important contribution that digestates could make in future to overall UK ammonia emissions, additional work is required to investigate alternative methods to further reduce ammonia emissions to arable land (e.g. acidification) to maximise the nutrient value of digestate, without greatly increasing costs or incurring other disadvantages.

Nitrous oxide losses from the food-based digestates were low (0.45 ± 0.15% of total N applied), with measured emission factors all less than the current IPCC default value of 1%. Methane emissions from digestates were lower than from livestock slurry, which is probably because most of the 'available' carbon in the digestates had already been lost during the anaerobic digestion process. The application of both digestate and livestock slurry resulted in elevated CO_2 emissions immediately following spreading most likely due to the supply of both readily decomposable C and readily available N, which stimulated microbial activity. Overwinter nitrate leaching losses from food-based digestate were similar in magnitude to those from pig slurry but much greater than those from pig FYM or compost. Phosphorus leaching losses were low and similar to those measured on the untreated control treatment and no viable *E.coli* were detected in the drainage waters from any of the treatments.

The results from *DC-Agri* strongly suggest that digestate users should be advised, where practically possible, to apply digestates using precision application methods such as bandspreading/trailing shoe or shallow injection. Also, digestates should be applied to crops when there is an N demand, commonly in the spring/summer, and should only be applied in the autumn to crops which are actively growing (e.g. oilseed rape and grass), with application rates controlled to match crop N requirements.

5.2 Compost

Atmospheric emissions (i.e. ammonia, nitrous oxide, methane) and leaching losses (nitrate, soluble P) from compost (both green and green/food) were found to be low and no viable *E.coli* were detected in drainage waters indicating that in these terms compost can be considered as an 'environmentally benign' material. Because of its low readily available N content, compost applications should be seen as a means to build up long-term (organic) soil N reserves rather than as a short-term replacement for mineral fertiliser.

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Appendix I: Results for the nitrogen supply sites (WP2.1)

Table 1 Baseline topsoil characteristics of the N supply sites (WP2.1)

Determinand*	1. Aberaeron	2. Aberdeen	3. Ayr	4. Beith	5. Brawdy	6. East Malling	7. Gleadthorpe	8. Harper Adams
pH	5.3	6.0	5.1	6.0	5.8	6.5	5.8	7.2
Sand (%)	25	63	54	30	42	51	63	74
Silt (%)	46	25	29	39	31	35	29	14
Clay (%)	29	12	17	31	27	14	8	12
Texture Classification	Clay loam	Sandy loam	Sandy loam	Clay loam	Clay loam	Sandy loam	Sandy loam	Sandy loam
Extractable P: mg/l (ADAS Index)[b]	19 (2)	54 (4)	39 (3)	44 (3)	18 (2)	23 (2)	34 (3)	45 (3)
Extractable K: mg/l (ADAS Index)[b]	87 (1)	136 (2-)	154 (2-)	134 (2-)	110 (1)	194 (2+)	130 (2-)	194 (2+)
Extractable Mg: mg/l (ADAS Index)[b]	38 (1)	84 (2)	175 (3)	207 (4)	58 (2)	72 (2)	87 (2)	94 (2)
Extractable SO_4-S (mg/l)	49	23	46	42	70	36	715	22
Total N (% dm)	0.39	0.24	0.21	0.62	0.15	0.09	0.14	0.16
Organic C (% dm)	4.03	2.99	2.43	6.66	2.43	0.73	1.68	2.01
Organic Matter[a] (% dm)	6.95	5.15	4.20	11.5	4.20	1.26	2.89	3.47
Loss on ignition (%)	9.97	8.40	6.67	15.2	6.73	2.93	3.20	4.20

* mg/l = milligrams/litre; dm = dry matter
[a] Organic carbon multiplied by 1.724 (MAFF, 1986)
[b] ADAS Indices (Defra, 2010b) refer to the relative amounts of soil nutrients which are available to plants and range from 0 (deficient) to 9 (very large).

Table 1 (cont.) Baseline topsoil characteristics of the N supply sites (WP2.1)

Determinand*	**9. Loddington**	**10. Newark**	**11. Morpeth**	**12. North Wyke**	**13. Pwllpeiran**	**14. Wensum**	**15. Devizes**
pH	6.5	6.8	7.3	5.5	5.1	6.7	7.9
Sand (%)	35	22	42	32	36	78	19
Silt (%)	27	42	26	40	36	11	50
Clay (%)	38	36	32	28	28	11	31
Texture Classification	Clay	Clay	Clay loam	Clay loam	Clay loam	Sandy loam	Silty clay loam
Extractable P: mg/l (ADAS Index)[b]	11 (1)	11 (1)	17 (2)	13 (1)	24 (3)	24 (2)	21 (2)
Extractable K: mg/l (ADAS Index)[b]	112 (1)	262 (3)	137 (2-)	122 (2-)	75 (1)	151 (2-)	366 (3)
Extractable Mg: mg/l (ADAS Index)[b]	133 (3)	407 (6)	92 (2)	115 (3)	78 (2)	35 (1)	71 (2)
Extractable SO_4-S (mg/l)	28	24	278	42	35	16	79
Total N (% dm)	0.26	0.25	0.30	0.40	0.50	0.20	0.35
Organic C (% dm)	2.57	2.44	3.04	6.93	4.7	1.3	2.90
Organic Matter[a] (% dm)	4.42	4.20	5.24	12.0	10.7	1.7	5.00
Loss on ignition (%)	7.87	5.10	8.20	9.57	11.7	3.2	9.90

* mg/l = milligrams/litre; dm = dry matter

[a] Organic carbon multiplied by 1.724 (MAFF, 1986)

[b] ADAS Indices (Defra, 2010b) refer to the relative amounts of soil nutrients which are available to plants and range from 0 (deficient) to 9 (very large).

Table 2 Organic material analyses at the N supply sites (WP2.1).

Site 1. Aberaeron – Autumn 2013 (25th September 2013)

Determinand	Unit+	Food-based digestate	Cattle slurry
pH	-	8.5	8.1
Dry Matter	%	3.58	5.56
Total Nitrogen (N)	kg/t fw	4.67	2.92
Readily Available Nitrogen *(% of total Nitrogen)*	kg/t fw	3.77 *(81%)*	1.69 *(58%)*
Total Phosphate (P_2O_5)	kg/t fw	0.91	0.97
Total Potash (K_2O)	kg/t fw	1.71	3.15
Total Magnesium (MgO)	kg/t fw	0.17	0.62
Total Sulphur (SO_3)	kg/t fw	0.37	0.58
Total Calcium	kg/t fw	1.53	1.29

Site 1. Aberaeron – Spring 2014 (19th March 2014)

Determinand	Unit+	Food-based digestate	Cattle slurry
pH	-	8.4	8.2
Dry Matter	%	2.11	4.79
Total Nitrogen (N)	kg/t fw	4.41	3.10
Readily Available Nitrogen *(% of total Nitrogen)*	kg/t fw	3.08 *(70%)*	1.83 *(59%)*
Total Phosphate (P_2O_5)	kg/t fw	0.36	0.87
Total Potash (K_2O)	kg/t fw	1.89	3.49
Total Magnesium (MgO)	kg/t fw	0.15	0.67
Total Sulphur (SO_3)	kg/t fw	0.34	0.69
Total Calcium	kg/t fw	0.75	1.35

Site 2. Aberdeen – Early spring 2013 (30th April 2013)

Determinand	Unit+	Food-based digestate	Manure-based digestate	Cattle slurry
pH	-	8.32	7.92	7.58
Dry Matter	%	2.33	3.64	4.04
Total Nitrogen (N)	kg/t fw	5.65	1.61	2.42
Readily Available Nitrogen *(% of total Nitrogen)*	kg/t fw	4.04 *(72%)*	0.90 *(56%)*	1.29 *(53%)*
Total Phosphate (P_2O_5)	kg/t fw	0.70	0.15	0.64
Total Potash (K_2O)	kg/t fw	1.73	2.22	2.32
Total Magnesium (MgO)	kg/t fw	0.03	0.21	0.44
Total Sulphur (SO_3)	kg/t fw	0.28	0.22	0.48
Total Calcium	kg/t fw	0.64	0.36	0.67

Site 2. Aberdeen – Late spring 2013 (6th June 2013)

Determinand	Unit+	Food-based digestate	Manure-based digestate	Cattle slurry
pH	-	8.34	7.39	7.75
Dry Matter	%	2.00	4.28	4.55
Total Nitrogen (N)	kg/t fw	5.81	1.39	3.23
Readily Available Nitrogen *(% of total Nitrogen)*	kg/t fw	4.88 *(84%)*	0.83 *(60%)*	1.72 *(53%)*
Total Phosphate (P_2O_5)	kg/t fw	0.67	0.79	0.89
Total Potash (K_2O)	kg/t fw	2.14	2.06	3.19
Total Magnesium (MgO)	kg/t fw	0.02	0.68	0.75
Total Sulphur (SO_3)	kg/t fw	0.26	0.55	0.69
Total Calcium	kg/t fw	0.48	0.64	1.03

Site 3. Ayr – Autumn 2010 (September 2010)

Determinand	Unit+	Food-based digestate	Manure-based digestate	Cattle slurry
pH	-	7.9	7.9	6.8
Dry Matter	%	2.43	0.67	3.9
Total Nitrogen (N)	kg/t fw	4.11	0.88	2.69
Readily Available Nitrogen *(% of total Nitrogen)*	kg/t fw	3.39 *(82%)*	0.73 *(83%)*	1.41 *(52%)*
Total Phosphate (P_2O_5)	kg/t fw	0.43	0.07	0.58
Total Potash (K_2O)	kg/t fw	2.05	1.27	1.97
Total Magnesium (MgO)	kg/t fw	0.06	0.11	0.45
Total Sulphur (SO_3)	kg/t fw	0.24	0.11	0.56
Total Calcium	kg/t fw	0.40	0.14	0.57

Site 3. Ayr – Spring 2011 (9th April 2011)

Determinand	Unit+	Food-based digestate	Manure-based digestate	Cattle slurry
pH	-	7.9	7.9	6.9
Dry Matter	%	1.93	0.68	4.41
Total Nitrogen (N)	kg/t fw	3.57	0.90	2.69
Readily Available Nitrogen *(% of total Nitrogen)*	kg/t fw	2.99 *(84%)*	0.72 *(81%)*	1.37 *(51%)*
Total Phosphate (P_2O_5)	kg/t fw	0.34	0.06	0.64
Total Potash (K_2O)	kg/t fw	1.90	1.24	2.08
Total Magnesium (MgO)	kg/t fw	0.06	0.10	0.49
Total Sulphur (SO_3)	kg/t fw	0.20	0.10	0.62
Total Calcium	kg/t fw	0.32	0.14	0.62

Site 4. Beith – Autumn 2013 (11th September 2013)

Determinand	Unit+	Food-based digestate	Cattle slurry
pH	-	8.5	7.8
Dry Matter	%	4.22	6.57
Total Nitrogen (N)	kg/t fw	3.71	2.73
Readily Available Nitrogen *(% of total Nitrogen)*	kg/t fw	2.54 *(68%)*	1.34 *(49%)*
Total Phosphate (P_2O_5)	kg/t fw	0.94	0.83
Total Potash (K_2O)	kg/t fw	1.59	2.38
Total Magnesium (MgO)	kg/t fw	0.25	0.73
Total Sulphur (SO_3)	kg/t fw	1.04	0.64
Total Calcium	kg/t fw	1.05	1.12

Site 4. Beith – Spring 2014 (2nd April 2014)

Determinand	Unit+	Food-based digestate	Cattle slurry
pH	-	8.4	7.5
Dry Matter	%	4.12	5.10
Total Nitrogen (N)	kg/t fw	3.51	2.87
Readily Available Nitrogen *(% of total Nitrogen)*	kg/t fw	2.48 *(71%)*	1.21 *(42%)*
Total Phosphate (P_2O_5)	kg/t fw	0.66	0.81
Total Potash (K_2O)	kg/t fw	1.57	2.59
Total Magnesium (MgO)	kg/t fw	0.25	0.80
Total Sulphur (SO_3)	kg/t fw	0.72	0.69
Total Calcium	kg/t fw	1.06	1.39

Site 5. Brawdy – Autumn 2010 (30th September 2010)

Determinand	Unit+	Food-based digestate	Manure-based digestate	Cattle slurry
pH	-	7.8	7.9	6.5
Dry Matter	%	4.73	7.46	7.50
Total Nitrogen (N)	kg/t fw	5.39	3.72	2.49
Readily Available Nitrogen *(% of total Nitrogen)*	kg/t fw	3.52 (65%)	1.24 (33%)	1.16 (47%)
Total Phosphate (P_2O_5)	kg/t fw	1.66	1.84	0.65
Total Potash (K_2O)	kg/t fw	1.92	1.81	2.13
Total Magnesium (MgO)	kg/t fw	0.33	1.22	0.41
Total Sulphur (SO_3)	kg/t fw	0.55	0.86	0.52
Total Calcium	kg/t fw	2.33	1.44	0.86

Site 5. Brawdy – Spring 2011 (9th April 2011)

Determinand	Unit+	Food-based digestate	Manure-based digestate	Cattle slurry
pH	-	8.5	8.0	7.3
Dry Matter	%	4.51	6.87	7.80
Total Nitrogen (N)	kg/t fw	4.86	4.06	2.63
Readily Available Nitrogen *(% of total Nitrogen)*	kg/t fw	3.23 *(66%)*	1.47 *(36%)*	1.23 *(47%)*
Total Phosphate (P_2O_5)	kg/t fw	0.50	2.24	0.73
Total Potash (K_2O)	kg/t fw	1.81	2.27	2.14
Total Magnesium (MgO)	kg/t fw	0.04	1.45	0.46
Total Sulphur (SO_3)	kg/t fw	0.48	1.12	0.69
Total Calcium	kg/t fw	0.49	1.87	0.63

Site 6. East Malling – Autumn 2012 (10th October 2012)

Determinand	Unit+	'Food'-based digestate	'Manure'-based digestate	Cattle slurry
pH	-	7.75	8.70	7.26
Dry Matter	%	5.80	2.37	3.39
Total Nitrogen (N)	kg/t fw	4.49	5.86	2.30
Readily Available Nitrogen *(% of total Nitrogen)*	kg/t fw	2.04 *(45%)*	5.17 *(88%)*	1.29 *(56%)*
Total Phosphate (P_2O_5)	kg/t fw	1.79	0.42	0.38
Total Potash (K_2O)	kg/t fw	3.07	2.74	1.98
Total Magnesium (MgO)	kg/t fw	0.65	0.02	0.27
Total Sulphur (SO_3)	kg/t fw	0.72	0.47	0.38
Total Calcium	kg/t fw	3.10	0.18	1.03

Site 6. East Malling – Spring 2013 (28th March 2013)

Determinand	Unit+	'Food'-based digestate	'Manure'-based digestate	Cattle slurry
pH	-	7.88	8.73	7.30
Dry Matter	%	6.06	4.39	4.57
Total Nitrogen (N)	kg/t fw	4.38	6.01	2.21
Readily Available Nitrogen *(% of total Nitrogen)*	kg/t fw	2.15 *(49%)*	5.11 *(85%)*	1.25 *(57%)*
Total Phosphate (P_2O_5)	kg/t fw	2.84	0.54	0.77
Total Potash (K_2O)	kg/t fw	4.97	2.76	2.06
Total Magnesium (MgO)	kg/t fw	0.94	0.02	0.53
Total Sulphur (SO_3)	kg/t fw	1.28	0.54	0.63
Total Calcium	kg/t fw	4.15	0.30	2.46

Site 7. Gleadthorpe – Early spring 2011 (24th February 2011)

Determinand	Unit+	Food-based digestate	Manure-based digestate	Cattle slurry
pH	-	8.0	7.9	6.7
Dry Matter	%	3.98	2.18	7.03
Total Nitrogen (N)	kg/t fw	4.47	2.17	3.07
Readily Available Nitrogen *(% of total Nitrogen)*	kg/t fw	3.32 *(74%)*	1.27 *(58%)*	1.54 *(50%)*
Total Phosphate (P_2O_5)	kg/t fw	0.45	0.38	0.71
Total Potash (K_2O)	kg/t fw	1.98	1.90	1.62
Total Magnesium (MgO)	kg/t fw	0.28	0.36	0.63
Total Sulphur (SO_3)	kg/t fw	0.82	0.33	3.93
Total Calcium	kg/t fw	0.68	0.34	2.74

Site 7. Gleadthorpe – Late spring 2011 (30th March 2011)

Determinand	Unit+	Food-based digestate	Manure-based digestate	Cattle slurry
pH	-	7.9	8.0	7.0
Dry Matter	%	2.80	2.27	5.12
Total Nitrogen (N)	kg/t fw	4.13	2.02	2.61
Readily Available Nitrogen *(% of total Nitrogen)*	kg/t fw	3.18 *(77%)*	1.23 *(60%)*	1.24 *(48%)*
Total Phosphate (P_2O_5)	kg/t fw	0.22	0.27	0.79
Total Potash (K_2O)	kg/t fw	1.73	1.64	1.94
Total Magnesium (MgO)	kg/t fw	0.09	0.27	0.70
Total Sulphur (SO_3)	kg/t fw	0.84	0.42	3.31
Total Calcium	kg/t fw	0.36	0.28	2.41

Site 8. Harper Adams – Early spring 2013 (31st January 2013)

Determinand	Unit+	Food-based digestate	Manure-based digestate	Cattle slurry
pH	-	7.98	8.18	7.53
Dry Matter	%	2.25	2.94	3.53
Total Nitrogen (N)	kg/t fw	3.60	3.43	2.21
Readily Available Nitrogen *(% of total Nitrogen)*	kg/t fw	2.94 *(82%)*	2.79 *(81%)*	1.37 *(62%)*
Total Phosphate (P_2O_5)	kg/t fw	0.27	0.16	0.37
Total Potash (K_2O)	kg/t fw	1.63	2.16	2.02
Total Magnesium (MgO)	kg/t fw	0.04	0.03	0.23
Total Sulphur (SO_3)	kg/t fw	0.34	0.34	0.46
Total Calcium	kg/t fw	0.25	0.24	0.89

Site 8. Harper Adams – Late spring 2013 (13th March 2013)

Determinand	Unit+	Food-based digestate	Manure-based digestate	Cattle slurry
pH	-	8.07	8.43	7.47
Dry Matter	%	2.72	7.50	2.74
Total Nitrogen (N)	kg/t fw	4.14	5.35	2.06
Readily Available Nitrogen *(% of total Nitrogen)*	kg/t fw	3.07 *(74%)*	3.27 *(61%)*	1.22 *(59%)*
Total Phosphate (P_2O_5)	kg/t fw	0.54	2.73	0.56
Total Potash (K_2O)	kg/t fw	2.44	4.71	2.05
Total Magnesium (MgO)	kg/t fw	0.13	1.15	0.33
Total Sulphur (SO_3)	kg/t fw	0.58	2.00	0.43
Total Calcium	kg/t fw	1.23	8.79	1.12

Site 9. Loddington – Autumn 2010 (30th September 2010)

Determinand	Unit+	Food-based digestate	Manure-based digestate	Cattle slurry
pH	-	8.5	8.3	7.4
Dry Matter	%	5.97	6.69	4.02
Total Nitrogen (N)	kg/t fw	6.20	3.98	2.01
Readily Available Nitrogen *(% of total Nitrogen)*	kg/t fw	4.18 (68%)	2.19 (55%)	0.92 (46%)
Total Phosphate (P_2O_5)	kg/t fw	0.74	1.18	0.64
Total Potash (K_2O)	kg/t fw	1.92	3.19	2.46
Total Magnesium (MgO)	kg/t fw	0.19	0.66	0.55
Total Sulphur (SO_3)	kg/t fw	0.47	1.42	0.66
Total Calcium	kg/t fw	1.37	1.15	1.02

Site 9. Loddington – Spring 2011 (18th March 2011)

Determinand	Unit+	Food-based digestate	Manure-based digestate	Cattle slurry
pH	-	8.7	7.9	7.3
Dry Matter	%	1.34	7.46	7.17
Total Nitrogen (N)	kg/t fw	4.32	4.19	3.46
Readily Available Nitrogen *(% of total Nitrogen)*	kg/t fw	3.70 *(86%)*	1.91 *(46%)*	1.23 *(36%)*
Total Phosphate (P_2O_5)	kg/t fw	0.27	1.28	1.58
Total Potash (K_2O)	kg/t fw	2.16	3.16	4.11
Total Magnesium (MgO)	kg/t fw	0.01	0.66	1.00
Total Sulphur (SO_3)	kg/t fw	0.25	1.28	0.52
Total Calcium	kg/t fw	0.15	1.28	2.41

Site 10. Newark – Autumn 2013 (9th October 2013)

Determinand	Unit+	Food-based digestate	Cattle slurry
pH	-	8.6	8.2
Dry Matter	%	4.61	9.42
Total Nitrogen (N)	kg/t fw	6.06	3.78
Readily Available Nitrogen *(% of total Nitrogen)*	kg/t fw	5.31 *(88%)*	1.96 *(52%)*
Total Phosphate (P_2O_5)	kg/t fw	0.89	1.02
Total Potash (K_2O)	kg/t fw	1.75	3.27
Total Magnesium (MgO)	kg/t fw	0.26	1.15
Total Sulphur (SO_3)	kg/t fw	0.57	0.96
Total Calcium	kg/t fw	1.42	1.84

Site 10. Newark – Spring 2014 (4th March 2014)

Determinand	Unit+	Food-based digestate	Cattle slurry
pH	-	8.2	8.0
Dry Matter	%	3.14	8.58
Total Nitrogen (N)	kg/t fw	6.02	4.33
Readily Available Nitrogen *(% of total Nitrogen)*	kg/t fw	4.35 *(72%)*	2.33 *(54%)*
Total Phosphate (P_2O_5)	kg/t fw	0.74	0.95
Total Potash (K_2O)	kg/t fw	1.71	3.13
Total Magnesium (MgO)	kg/t fw	0.28	1.06
Total Sulphur (SO_3)	kg/t fw	0.46	0.87
Total Calcium	kg/t fw	1.36	1.91

Site 11. Morpeth – Autumn 2012 (25th October 2012)

Determinand	Unit[+]	Food-based digestate	Manure-based digestate	Cattle slurry
pH	-	8.05	8.12	7.45
Dry Matter	%	4.86	1.40	1.58
Total Nitrogen (N)	kg/t fw	7.73	2.64	1.52
Readily Available Nitrogen *(% of total Nitrogen)*	kg/t fw	5.81 *(75%)*	2.19 *(83%)*	0.90 *(59%)*
Total Phosphate (P_2O_5)	kg/t fw	0.72	0.53	0.21
Total Potash (K_2O)	kg/t fw	1.31	2.01	2.82
Total Magnesium (MgO)	kg/t fw	0.05	0.33	0.17
Total Sulphur (SO_3)	kg/t fw	0.74	0.39	0.22
Total Calcium	kg/t fw	0.57	0.67	0.24

Site 11. Morpeth – Spring 2013 (22nd February 2013)

Determinand	Unit[+]	Food-based digestate	Manure-based digestate	Cattle slurry
pH	-	7.94	8.13	7.43
Dry Matter	%	4.08	2.11	1.42
Total Nitrogen (N)	kg/t fw	7.40	3.02	1.44
Readily Available Nitrogen *(% of total Nitrogen)*	kg/t fw	5.35 *(72%)*	2.08 *(69%)*	0.85 *(59%)*
Total Phosphate (P_2O_5)	kg/t fw	0.93	0.99	0.23
Total Potash (K_2O)	kg/t fw	1.82	2.80	1.82
Total Magnesium (MgO)	kg/t fw	0.08	0.60	0.20
Total Sulphur (SO_3)	kg/t fw	0.91	0.48	0.27
Total Calcium	kg/t fw	0.79	1.04	0.25

Site 12. North Wyke – Autumn 2011 (27th September 2011)

Determinand	Unit+	Food-based digestate	Manure-based digestate	Cattle slurry
pH	-	8.1	7.7	7.5
Dry Matter	%	4.99	5.76	4.10
Total Nitrogen (N)	kg/t fw	8.31	3.00	2.00
Readily Available Nitrogen *(% of total Nitrogen)*	kg/t fw	5.76 *(69%)*	1.48 *(49)*	0.90 *(45%)*
Total Phosphate (P_2O_5)	kg/t fw	1.12	1.08	0.44
Total Potash (K_2O)	kg/t fw	1.92	2.57	1.67
Total Magnesium (MgO)	kg/t fw	0.05	0.58	0.38
Total Sulphur (SO_3)	kg/t fw	1.15	0.80	0.35
Total Calcium	kg/t fw	1.31	1.17	0.82

Site 12. North Wyke – Spring 2012

Determinand	Unit+	Food-based digestate	Manure-based digestate	Cattle slurry
pH	-	8.1	7.3	8.2
Dry Matter	%	5.1	4.1	6.1
Total Nitrogen (N)	kg/t fw	7.99	2.73	2.58
Readily Available Nitrogen *(% of total Nitrogen)*	kg/t fw	5.84 *(73%)*	1.69 *(62%)*	1.44 *(56%)*
Total Phosphate (P_2O_5)	kg/t fw	1.01	0.69	0.76
Total Potash (K_2O)	kg/t fw	1.86	3.04	2.84
Total Magnesium (MgO)	kg/t fw	0.10	0.57	0.85
Total Sulphur (SO_3)	kg/t fw	0.85	0.40	2.08
Total Calcium	kg/t fw	1.76	0.95	3.46

Site 13. Pwllpeiran – Autumn 2011 (28th September 2011)

Determinand	Unit+	Food-based digestate	Manure-based digestate	Cattle slurry
pH	-	8.6	7.7	7.4
Dry Matter	%	0.66	0.44	1.68
Total Nitrogen (N)	kg/t fw	5.38	2.52	0.82
Readily Available Nitrogen *(% of total Nitrogen)*	kg/t fw	4.11 *(76%)*	1.07 *(42%)*	0.32 *(39%)*
Total Phosphate (P_2O_5)	kg/t fw	1.51	0.89	0.37
Total Potash (K_2O)	kg/t fw	1.93	2.08	1.38
Total Magnesium (MgO)	kg/t fw	0.17	0.68	0.27
Total Sulphur (SO_3)	kg/t fw	1.90	0.63	0.20
Total Calcium	kg/t fw	2.63	0.89	0.30

Site 13. Pwllpeiran – Spring 2012 (2nd May 2012)

Determinand	Unit+	Food-based digestate	Manure-based digestate	Cattle slurry
pH	-	8.4	7.6	7.0
Dry Matter	%	0.61	0.55	4.89
Total Nitrogen (N)	kg/t fw	5.44	2.42	2.25
Readily Available Nitrogen *(% of total Nitrogen)*	kg/t fw	3.90 *(72%)*	1.07 *(44%)*	1.20 *(53%)*
Total Phosphate (P_2O_5)	kg/t fw	1.76	0.99	0.62
Total Potash (K_2O)	kg/t fw	1.72	2.53	2.42
Total Magnesium (MgO)	kg/t fw	0.28	0.80	0.38
Total Sulphur (SO_3)	kg/t fw	0.45	0.73	0.38
Total Calcium	kg/t fw	2.81	1.03	0.53

Site 14. Wensum – Autumn 2011 (25th September 2011)

Determinand	Unit+	Food-based digestate	Manure-based digestate	Pig slurry
pH	-	8.8	7.8	7.5
Dry Matter	%	5.4	5.1	2.3
Total Nitrogen (N)	kg/t fw	7.8	3.2	3.0
Readily Available Nitrogen *(% of total Nitrogen)*	kg/t fw	6.3 (82)	1.8 *(54)*	2.2 *(75)*
Total Phosphate (P_2O_5)	kg/t fw	1.15	0.96	0.82
Total Potash (K_2O)	kg/t fw	1.82	2.44	1.30
Total Magnesium (MgO)	kg/t fw	0.13	0.50	0.37
Total Sulphur (SO_3)	kg/t fw	0.68	0.65	0.55
Total Calcium	kg/t fw	2.33	0.99	0.84

Site 14. Wensum – Spring 2012 (6th March 2012)

Determinand	Unit+	Food-based digestate	Manure-based digestate	Pig slurry
pH	-	8.7	7.7	8.0
Dry Matter	%	0.4	0.4	2.71
Total Nitrogen (N)	kg/t fw	6.89	2.84	2.59
Readily Available Nitrogen *(% of total Nitrogen)*	kg/t fw	6.16 *(89%)*	*1.94* *(68%)*	2.24 *(87%)*
Total Phosphate (P_2O_5)	kg/t fw	0.92	0.92	0.41
Total Potash (K_2O)	kg/t fw	2.05	2.63	1.27
Total Magnesium (MgO)	kg/t fw	0.07	0.48	0.15
Total Sulphur (SO_3)	kg/t fw	0.60	0.58	0.40
Total Calcium	kg/t fw	1.39	0.93	0.49

Site 15. Devizes – autumn 2012 (29th September 2012)

Determinand	Unit+	Food-based digestate	Manure-based digestate	Cattle slurry
pH	-	8.17	8.00	7.24
Dry Matter	%	3.99	5.03	7.25
Total Nitrogen (N)	kg/t fw	5.12	4.14	3.20
Readily Available Nitrogen *(% of total Nitrogen)*	kg/t fw	3.20 *(63%)*	2.17 *(53%)*	1.72 *(54%)*
Total Phosphate (P_2O_5)	kg/t fw	1.20	0.87	0.97
Total Potash (K_2O)	kg/t fw	2.84	3.73	3.50
Total Magnesium (MgO)	kg/t fw	0.16	0.44	0.65
Total Sulphur (SO_3)	kg/t fw	0.77	0.58	1.00
Total Calcium	kg/t fw	2.65	1.34	1.76

Site 15. Devizes – spring 2013 (6th March 2013)

Determinand	Unit+	Food-based digestate	Manure-based digestate	Cattle slurry
pH	-	8.18	7.90	7.44
Dry Matter	%	3.46	4.94	5.94
Total Nitrogen (N)	kg/t fw	4.51	3.89	2.88
Readily Available Nitrogen *(% of total Nitrogen)*	kg/t fw	2.85 *(63%)*	2.12 *(55%)*	1.55 (54%)
Total Phosphate (P_2O_5)	kg/t fw	0.70	0.73	0.77
Total Potash (K_2O)	kg/t fw	2.30	4.05	3.09
Total Magnesium (MgO)	kg/t fw	0.11	0.30	0.56
Total Sulphur (SO_3)	kg/t fw	0.52	0.55	0.85
Total Calcium	kg/t fw	1.51	1.12	1.40

Table 3 Yields and N offtake at the N supply sites (WP2.1)

Treatment	Timing*	1.Aberaeron*		2.Aberdeen**		3.Ayr	
		Yield (t/ha)	N offtake (kg/ha)	Yield (t/ha)	N offtake (kg/ha)	Yield (t/ha)	N offtake (kg/ha)
Control		8.20^{a}	88.6^{a}	3.03^{a}	34.9^{a}	8.05	78.9^{ab}
Food-based digestate	Autumn	9.70^{b}	103.7^{b}	6.51^{e}	93.7^{d}	8.81	79.5^{ab}
	Spring	9.70^{b}	136.1^{b}	5.40^{d}	72.9^{c}	8.77	101.2^{c}
Manure-based digestate	Autumn	-	-	4.64^{bcd}	51.6^{b}	7.53	64.0^{a}
	Spring	-	-	4.32^{bc}	51.9^{b}	8.31	79.0^{ab}
Livestock slurry	Autumn	9.42^{b}	104.4^{b}	4.91^{cd}	55.4^{b}	8.20	75.2^{ab}
	Spring	9.23^{b}	114.9^{b}	3.99^{b}	48.1^{b}	8.88	91.1^{bc}
Fertiliser N response	N1	9.12	90.4	4.55	49.1	8.79	90.4
	N2	9.96	124.8	5.60	65.0	9.50	122.4
	N3	10.6	128.2	5.72	76.9	9.42	128.6
	N4	10.7	168.7	7.31	107	8.46	134.0
	N5	9.88	156.1	7.72	123	8.86	147.2
P		0.001	<0.001	*<0.001*	*<0.001*	*0.135*	*0.015*

*Anovas at Aberaeron also included broadcast and shallow injection treatments
**Timings at Aberdeen are pre- and post- establishment (not autumn and spring)
Different letters indicate significant (P<0.05) differences between organic material treatments

Table 3 (cont.). Yields and N offtake at the N supply sites (WP2.1)

Treatment	Timing*	4.Beith*		5.Brawdy		6.East Malling	
		Yield (t/ha)	N offtake (kg/ha)	Yield (t/ha)	N offtake (kg/ha)	Yield (t/ha)	N offtake (kg/ha)
Control		6.86	66.6	3.51^{a}	40.7^{a}	1.88^{a}	26.4^{a}
Food-based digestate	Autumn	6.67	78.6	3.76^{a}	44.7^{a}	1.95^{a}	39.8^{a}
	Spring	7.58	68.8	6.11^{c}	68.7^{c}	2.66^{a}	60.2^{b}
Manure-based digestate	Autumn	-	-	3.47^{a}	40.8^{a}	2.74^{a}	27.5^{a}
	Spring	-	-	5.05^{b}	56.2^{b}	4.64^{b}	35.5^{a}
Livestock slurry	Autumn	6.87	50.7	3.95^{a}	45.9^{a}	1.87^{a}	24.5^{a}
	Spring	7.46	66.8	5.55^{b}	61.5^{b}	2.13^{a}	28.0^{a}
Fertiliser N response	N1	7.62	79.7	6.04	72.3	1.88	45.35
	N2	8.02	87.3	8.08	95.7	3.40	67.41
	N3	8.39	107.4	8.00	98.7	5.19	95.29
	N4	9.12	124.1	10.52	154.4	6.29	111.38
	N5	9.87	142.1	11.17	171.2	6.88	123.56
P		*0.335*	*0.149*	*<0.001*	*<0.001*	*0.001*	*0.011*

*Anovas at Beith also included broadcast and shallow injection treatments
Different letters indicate significant (P<0.05) differences between organic material treatments

Table 3 (cont.). Yields and N offtake at the N supply sites (WP2.1)

Treatment	Timing*	7.Gleadthorpe*		8.Harper Adams*		9.Loddington	
		Yield (t/ha)	N offtake (kg/ha)	Yield (t/ha)	N offtake (kg/ha)	Yield (t/ha)	N offtake (kg/ha)
Control		57.8[a]	60.3[a]	3.13[a]	74.9	1.99[a]	27.5[a]
Food-based digestate	Autumn	69.3[b]	87.7[bc]	3.91[bcd]	101	2.94[bc]	37.4[ab]
	Spring	71.3[b]	90.3[bc]	4.20[d]	104	3.69[c]	49.2[b]
Manure-based digestate	Autumn	69.4[b]	84.3[b]	4.04b[cd]	96.6	2.47[ab]	31.6[a]
	Spring	72.4[b]	84.5[b]	4.44[cd]	97.8	3.46[c]	46.0[b]
Livestock slurry	Autumn	73.3[b]	97.6[c]	3.55[abc]	89.5	2.13[ab]	28.2[a]
	Spring	72.5[b]	97.8[c]	3.44[ab]	79.9	2.80[abc]	39.1[ab]
Fertiliser N response	N1	71.5	98.8	3.37	76.9	3.22	42.9
	N2	72.0	118	3.62	90.4	4.81	76.3
	N3	77.0	169	4.02	103	5.33	91.4
	N4	72.5	161	4.07	100	5.39	98.8
	N5	77.1	174	4.20	102	5.21	102.4
P		*<0.008*	*<0.001*	*<0.008*	*0.120*	*<0.007*	*0.014*

*Timings at Gleadthorpe and Harper Adams are early and late spring (not autumn and spring)
Different letters indicate significant (*P*<0.05) differences between organic material treatments

Table 3 (cont.). Yields and N offtake at the N supply sites (WP2.1)

Treatment	Timing*	10.Newark*		11.Morpeth		12.North Wyke**	
		Yield (t/ha)	N offtake (kg/ha)	Yield (t/ha)	N offtake (kg/ha)	Yield (t/ha)	N offtake (kg/ha)
Control		4.82	44.6	4.76[a]	52.6[a]	5.84	93.5
Food-based digestate	Autumn	4.95	46.6	7.75[d]	76.7[a]	6.51	128
	Spring	4.25	50.6	9.67[e]	119[c]	7.90	108
Manure-based digestate	Autumn	-	-	6.57[bc]	64.8[a]	5.84	101
	Spring	-	-	9.44[e]	109[bc]	6.00	93.7
Livestock slurry	Autumn	4.65	40.5	5.77[b]	60.7[a]	6.56	102
	Spring	5.08	49.2	6.67[c]	83.1[ab]	7.26	93.2
Fertiliser N response	N1	3.40	41.3	6.59	64.6	5.83	109
	N2	2.64	33.9	7.94	83.4	5.49	119
	N3	2.86	46.0	8.50	104	4.41	115
	N4	2.73	48.3	8.91	105	6.96	103
	N5	2.21	47.3	9.24	149	6.03	121
p		*0.829*	*0.626*	*<0.001*	*0.028*	*0.410*	*0.642*

*Anovas at Newark also included broadcast and shallow injection treatments
**Anovas at North Wyke also included treatments which were part of Defra project AC0116
Different letters indicate significant (*P*<0.05) differences between organic material treatments

Table 3 (cont.). Yields and N offtake at the N supply sites (WP2.1)

Treatment	Timing*	13.Pwllpeiran*		14.Wensum*		15.Devizes	
		Yield (t/ha)	N offtake (kg/ha)	Yield (t/ha)	N offtake (kg/ha)	Yield (t/ha)	N offtake (kg/ha)
Control		3.51[a]	54.6	4.24[a]	56.6[abcde]	4.39[a]	48.8[a]
Food-based digestate	Autumn	5.17[c]	66.2	5.75[def]	76.1[abcde]	5.21[b]	57.8[b]
	Spring	4.95[bc]	100.6	7.59[fg]	103.9[cde]	7.61[d]	87.1[d]
Manure-based digestate	Autumn	5.00[bc]	67.6	4.88[abc]	66.7[ab]	5.06[b]	56.7[b]
	Spring	4.34[abc]	83.9	5.91[cde]	74.8[bcde]	7.42[d]	86.6[d]
Livestock slurry	Autumn	4.24[abc]	57.2	5.79[cde]	81.2[bcde]	4.86[b]	55.8[ab]
	Spring	3.96[ab]	71.7	6.73[defg]	81.9[de]	6.37[c]	71.4[c]
Fertiliser N response	N1	5.82	54.6	5.95	78.7	6.71	75.1
	N2	6.86	92.4	6.89	96.1	8.46	104
	N3	7.00	109.9	7.36	118.0	9.54	129
	N4	6.27	137.4	7.27	122.4	10.25	153
	N5	6.51	137.5	6.78	131.3	10.32	169
p		*0.019*	*<0.001*	*<0.001*	*<0.001*	*<0.001*	*<0.001*

Different letters indicate significant ($P<0.05$) differences between organic material treatments.
*ANOVAs at Pwllpeiran and Wensum also included treatments which were part of Defra project AC0116

Appendix II. Nitrogen site results (WP2.2)

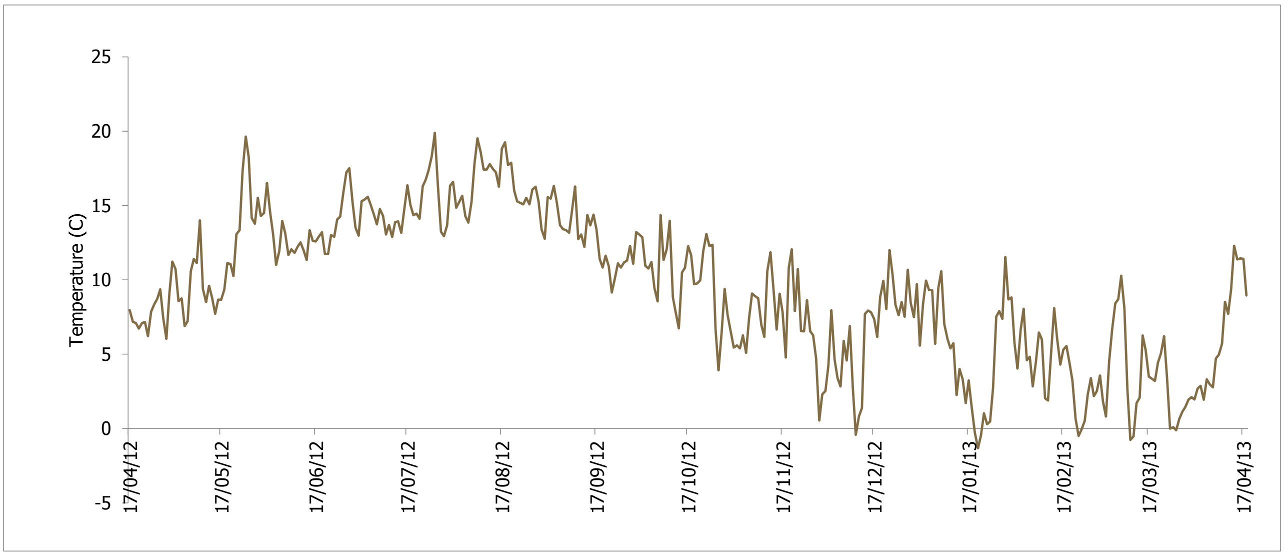


Figure 1. Mean daily air temperature at North Wyke (spring 2012-spring 2013)

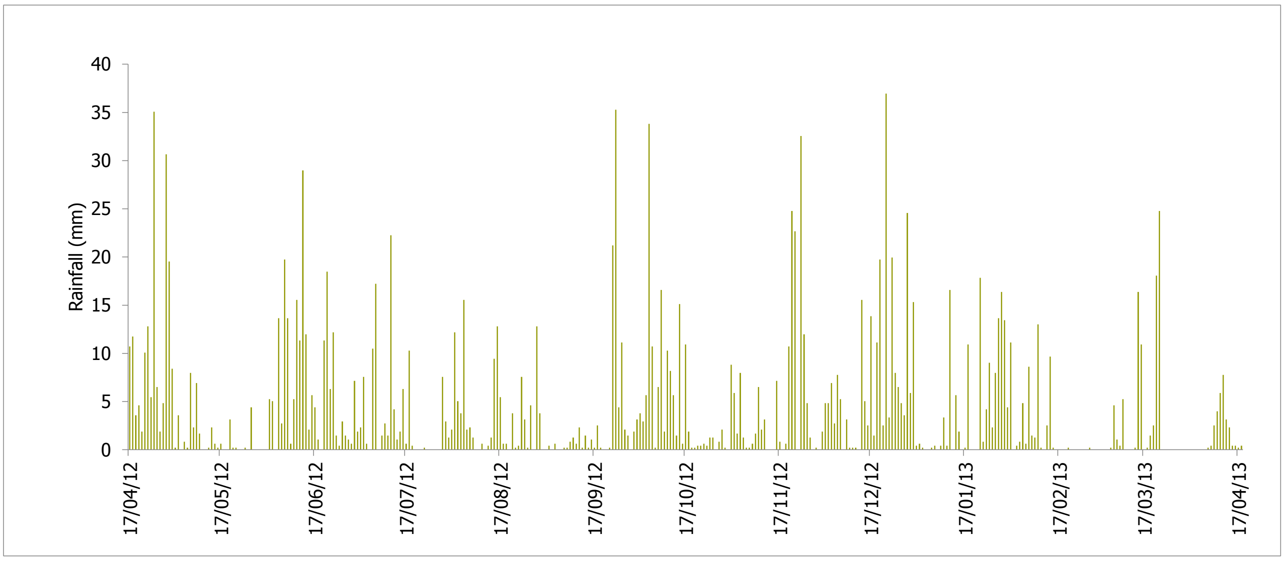


Figure 2. Daily rainfall at North Wyke (spring 2012-spring 2013)

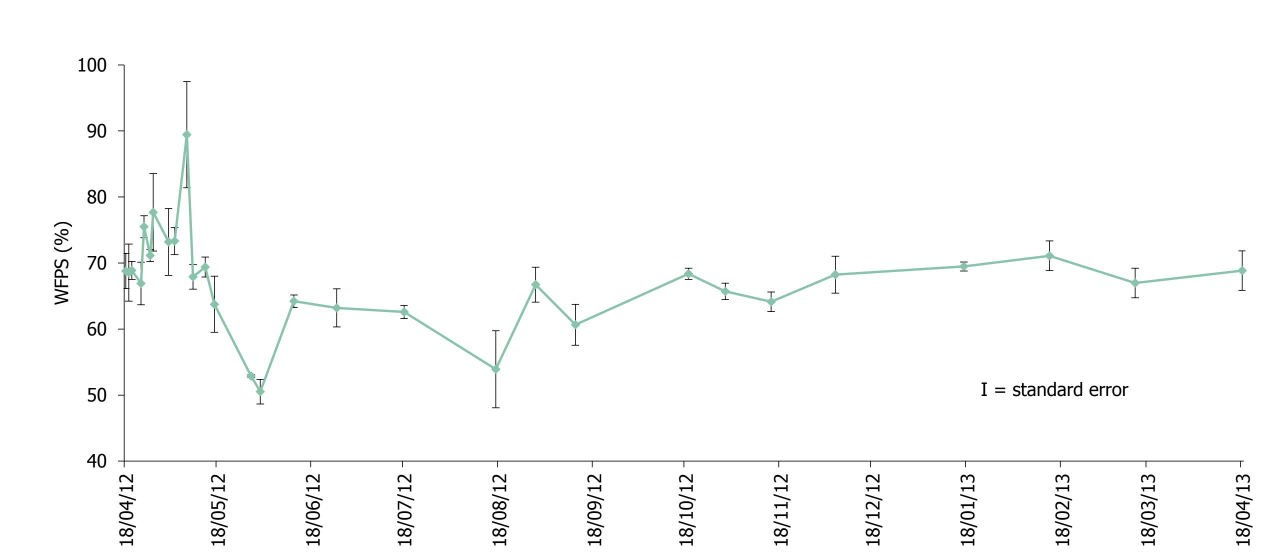
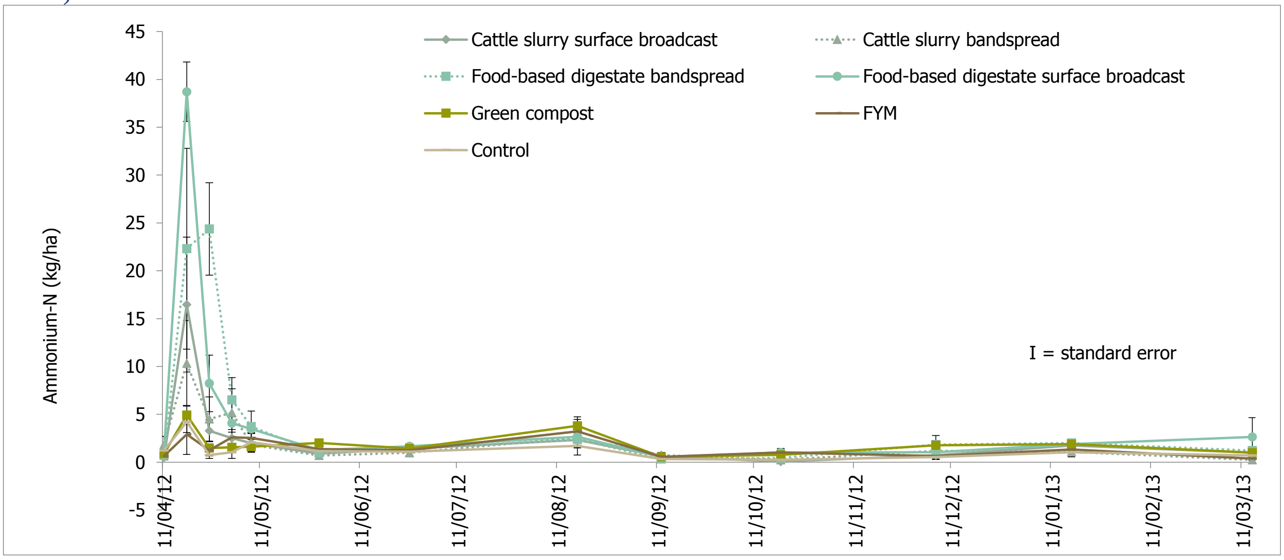


Figure 3. Water filled pore space at North Wyke (spring 2012-spring 2013)

a) Ammonium-N



b) Nitrate N

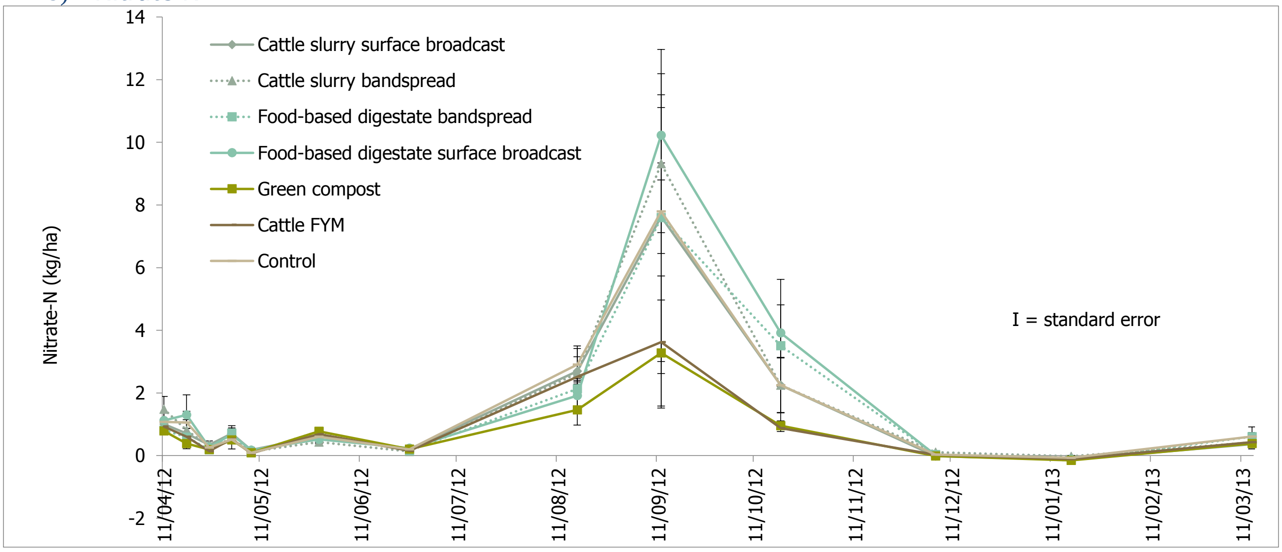


Figure 4. Soil mineral N at North Wyke (spring 2012-spring 2013)

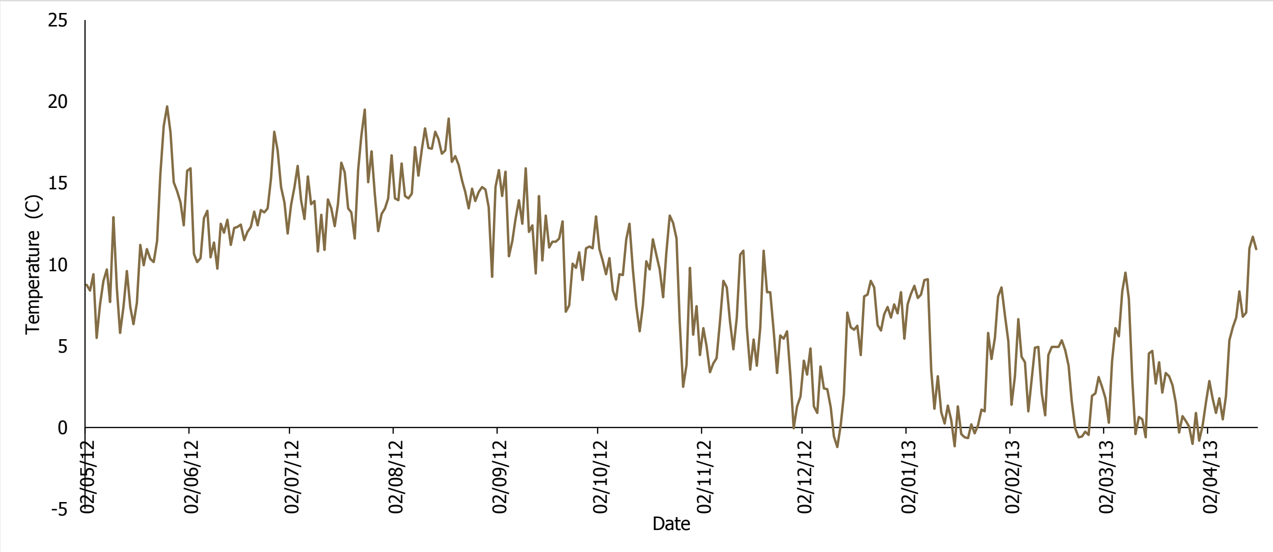


Figure 5. Mean daily air temperature at Pwllpeiran (spring 2012-spring 2013)

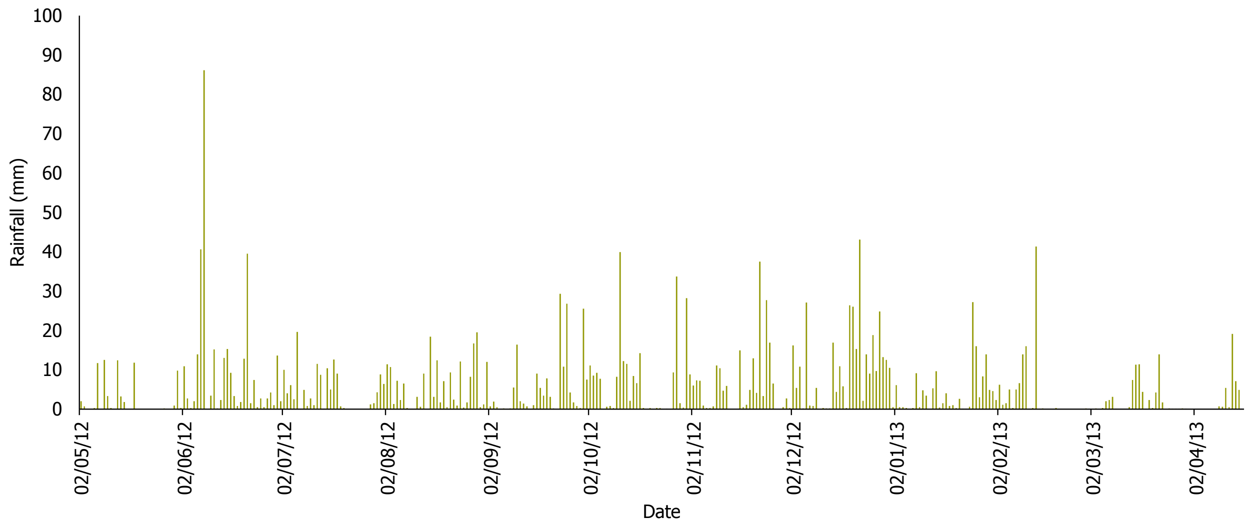


Figure 6. Daily rainfall at Pwllpeiran (spring 2012-spring 2013)

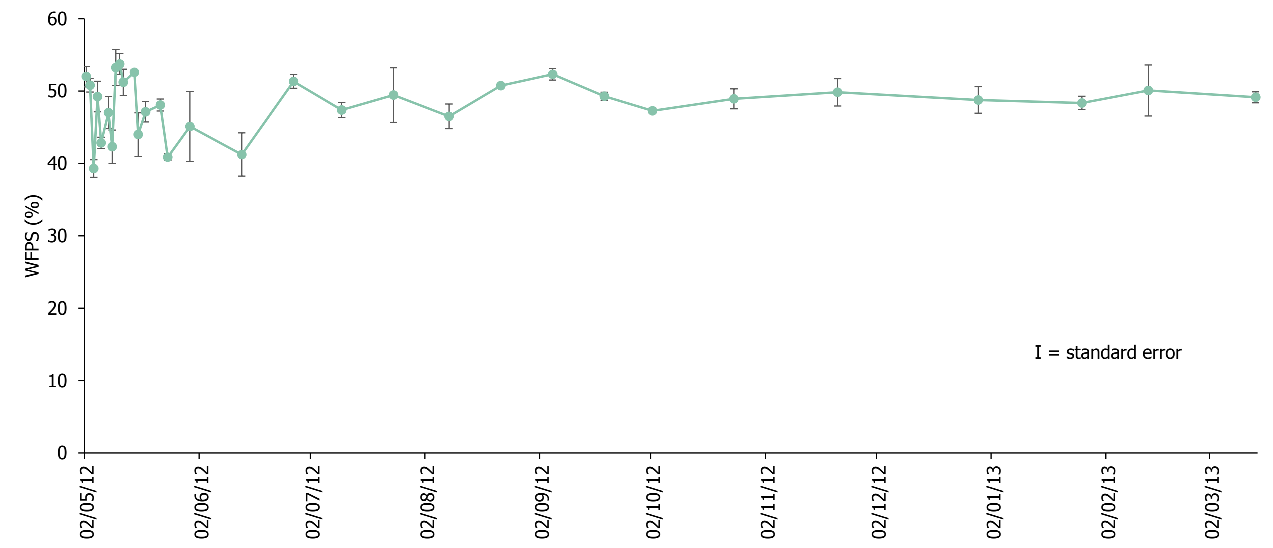
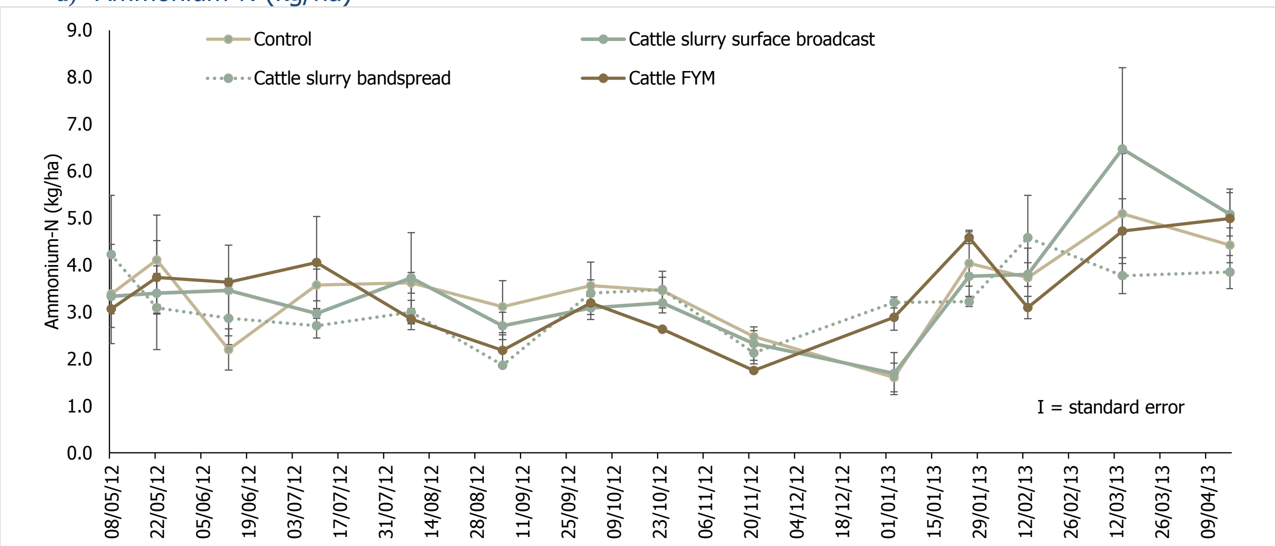


Figure 7. Water filled pore space at Pwllpeiran (spring 2012-spring 2013)

a) Ammonium-N (kg/ha)



b) Nitrate-N

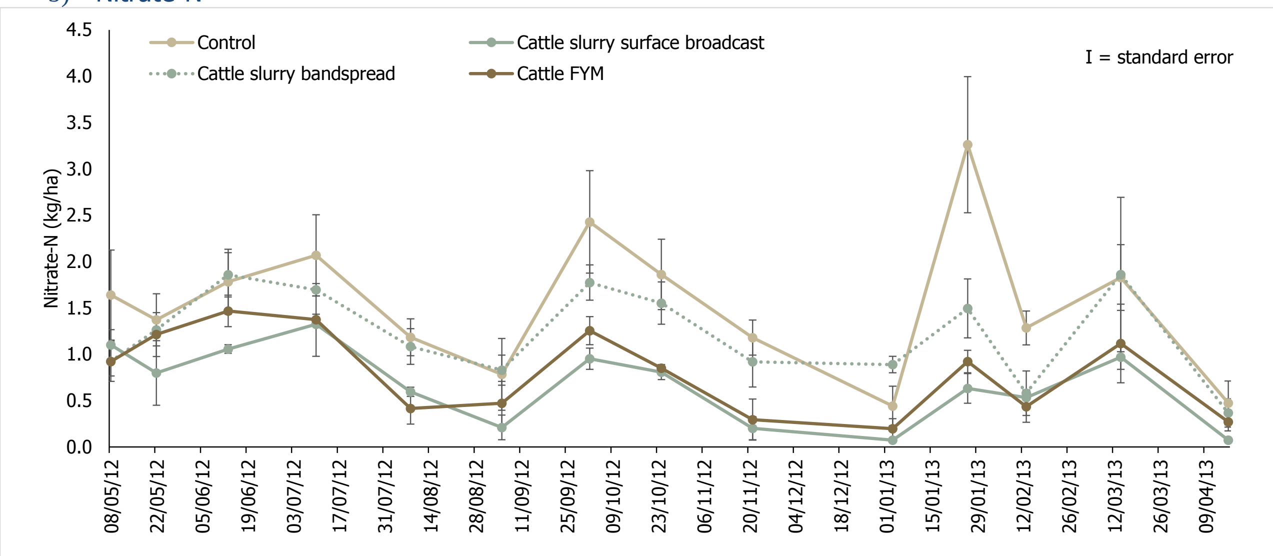


Figure 8. Soil mineral N at Pwllpeiran (spring 2012-spring 2013)

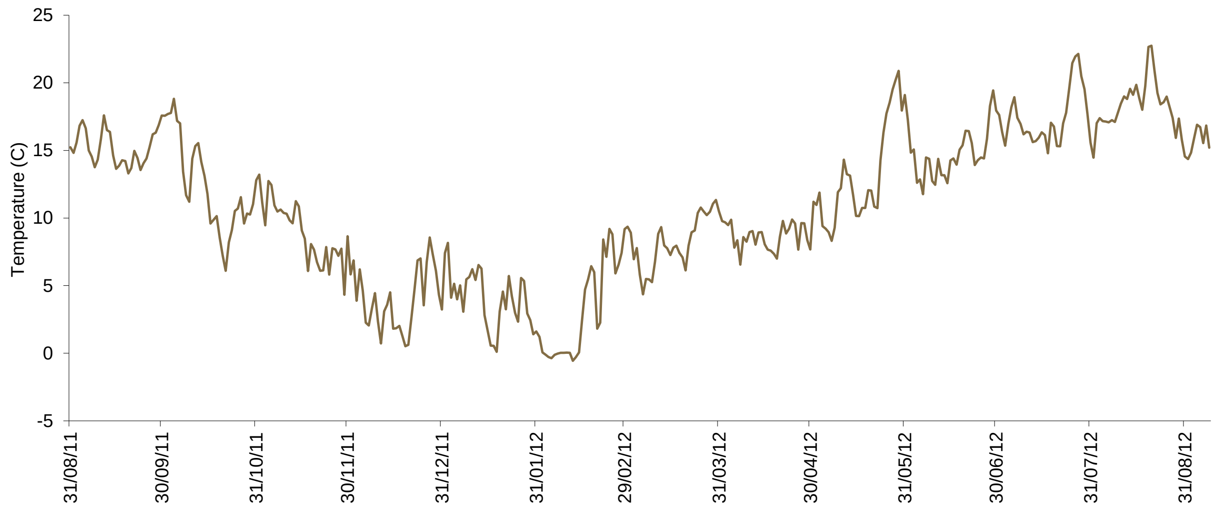


Figure 9. Mean air temperature at Wensum (autumn 2011- autumn 2012)

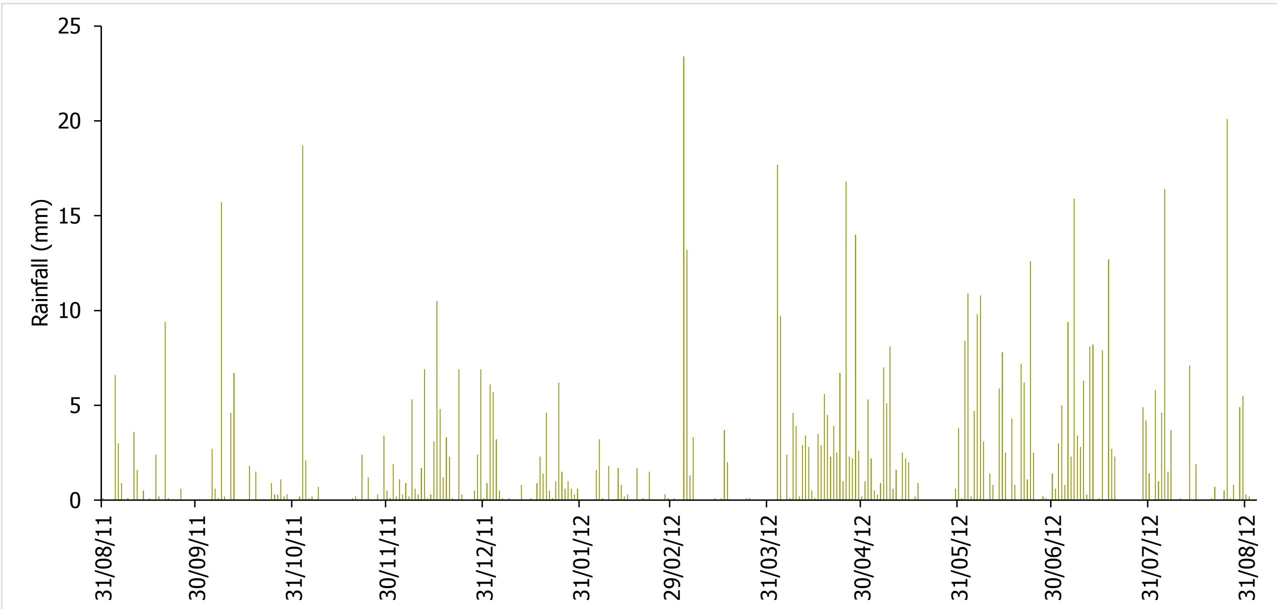


Figure 10. Daily rainfall at Wensum (autumn 2012- autumn 2013)

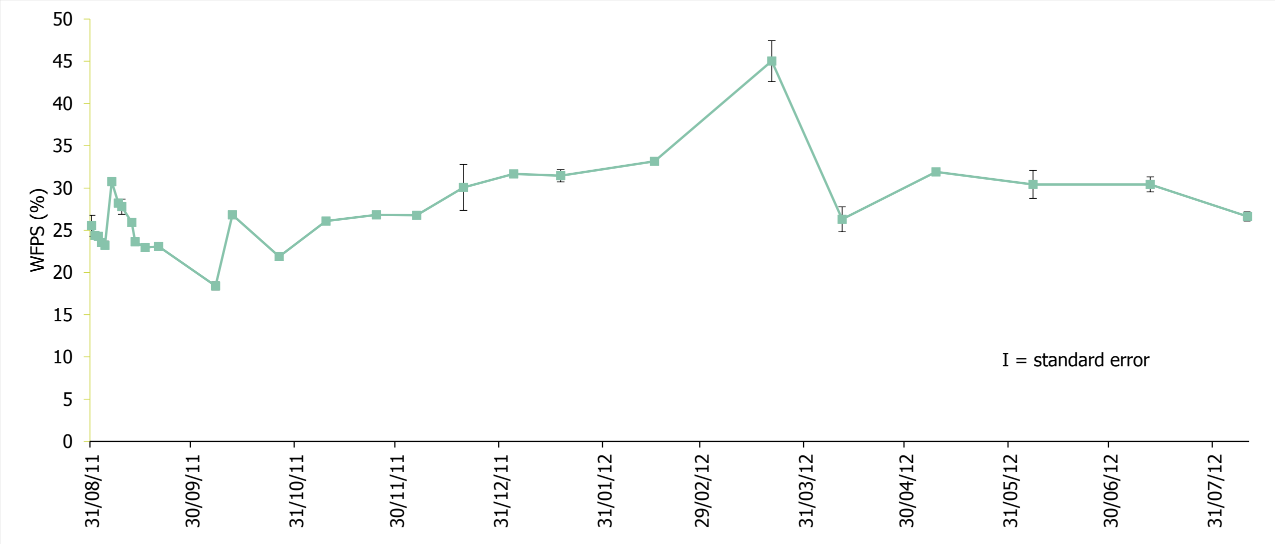
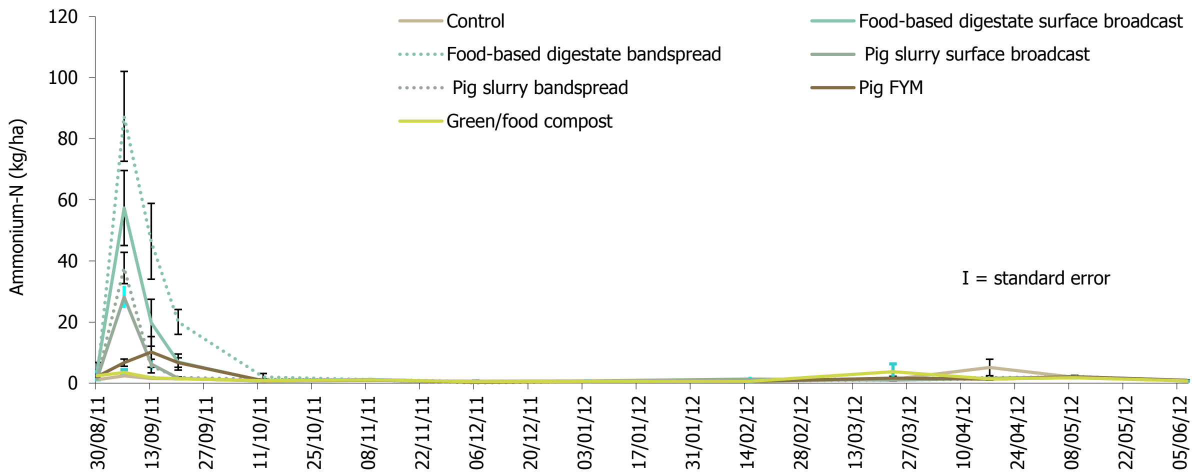


Figure 11. Water filled pore space at Wensum (autumn 2012- autumn 2013)

a) Ammonium-N



b) Nitrate N

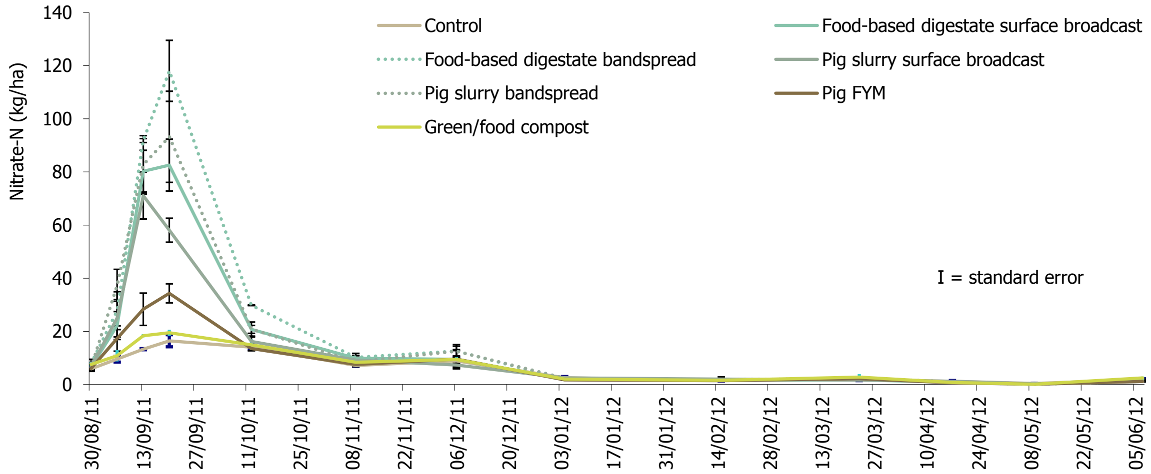


Figure 12. Soil mineral N at Wensum (autumn 2012- autumn 2013)

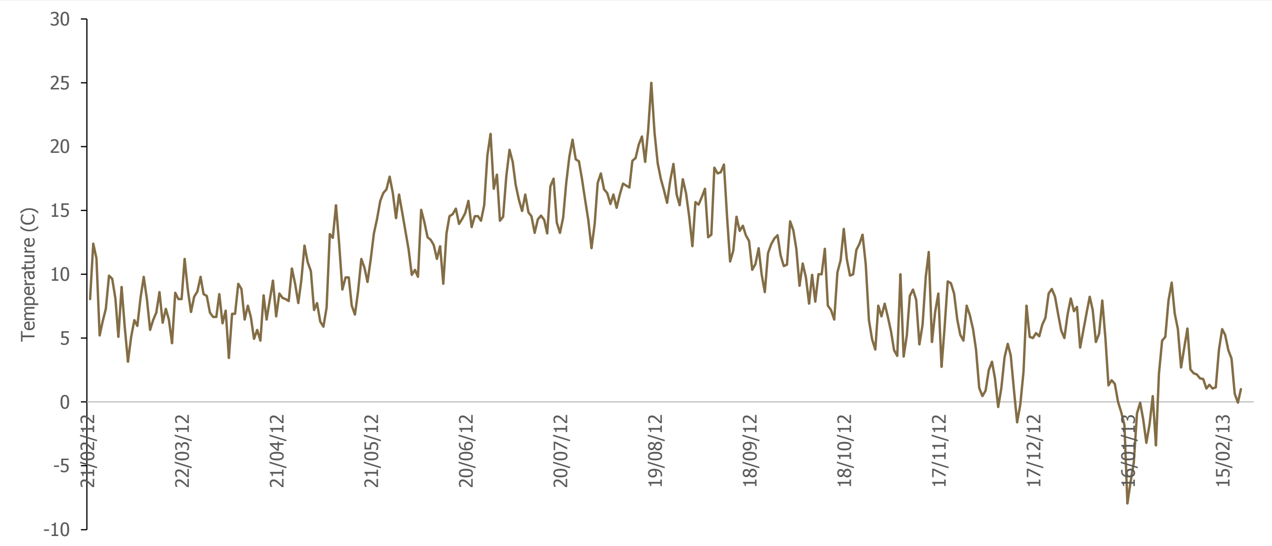


Figure 13. Mean daily air temperature at Wensum (spring 2012- spring 2013)

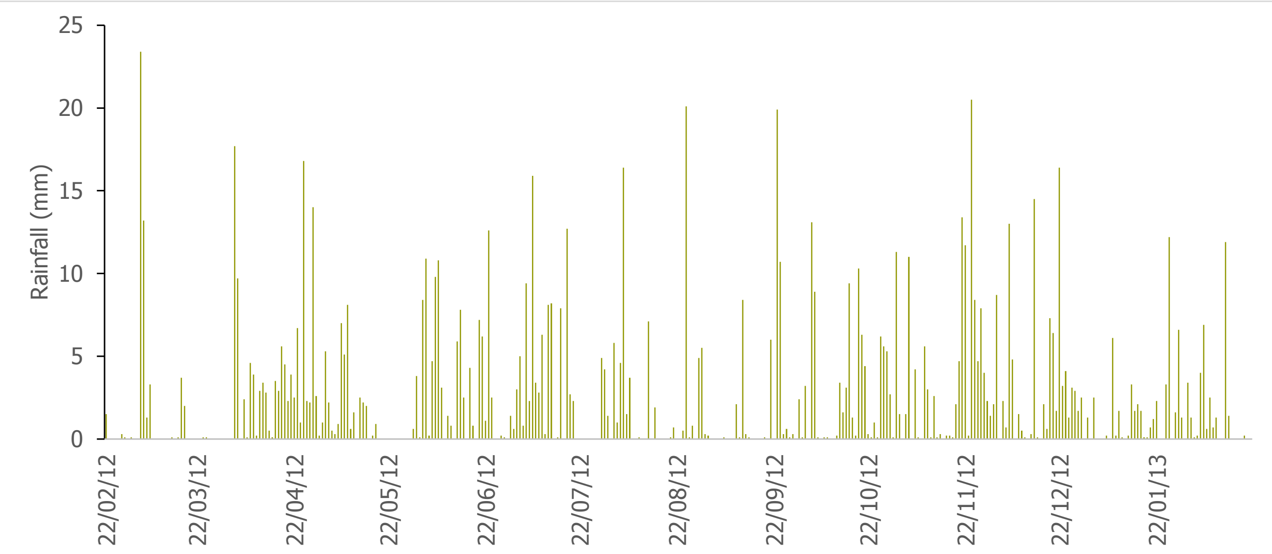


Figure 14. Daily rainfall at Wensum (spring 2012- spring 2013)

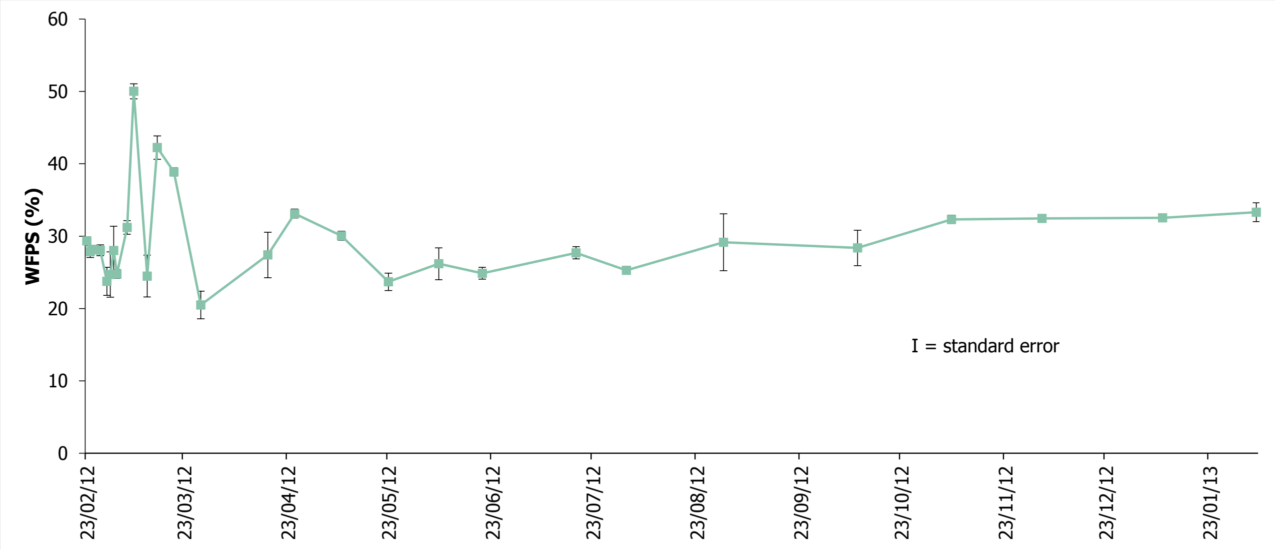
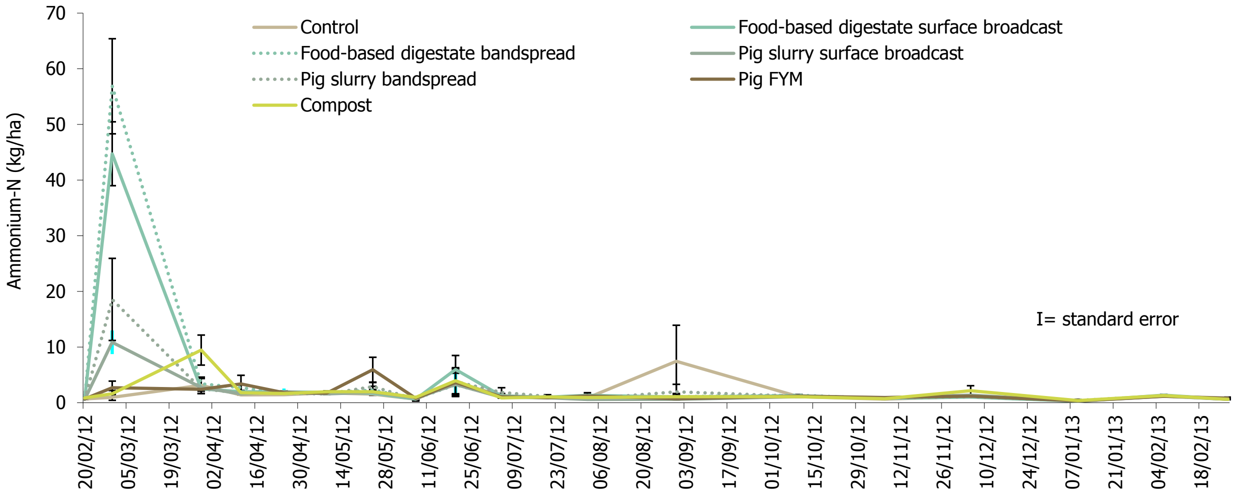


Figure 15. Water filled pore space at Wensum (spring 2012- spring 2013)

a) Ammonium-N



b) Nitrate N

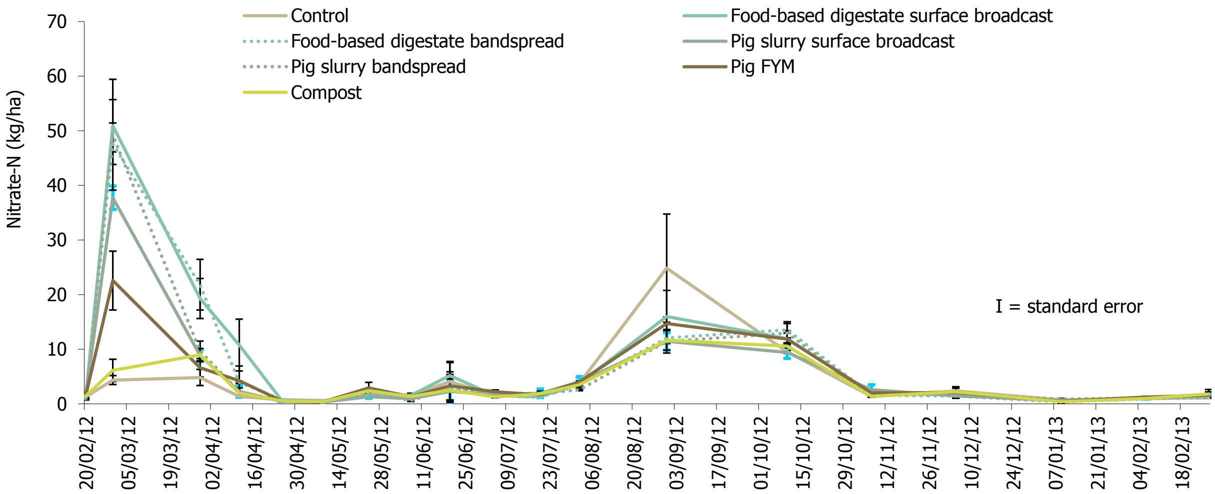


Figure 16. Soil mineral N at Wensum (spring 2012- spring 2013)

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